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SCIENTIFIC SURVEY
OF
Porto Rico and the Virgin Islands

VOLUME I—Part 1

History of the Survey—*N. L. Britton*
Geological Introduction—*C P. Berkey*
Geology of the San Juan District—*D. R. Semmes*

NEW YORK:
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1919

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HISTORY OF THE SURVEY

By N. L. Britton

Chairman of the Committee

In the latter part of the year 1913, subsequent to a discussion in the Council of the Academy relative to proposed extensions of the Academy's ordinary activities, a proposition for a scientific survey of Porto Rico was approved and referred to a committee consisting of Professors Boas, Britton, Crampton, Kemp and Poor, at the meeting of the Council in November of that year, at which meeting the Council appropriated $500 annually for five years for the purposes of this investigation. Dr. E. O. Hovey and Dr. R. W. Tower, Recording Secretaries of the Academy, have acted with the Committee. Professor Charles P. Berkey succeeded Professor Kemp as a member of the Committee in 1917. Mr. Emerson McMillin, at that time President of the Academy, kindly offered to assist the work, and has contributed $3,000. The Porto Rico Government was also interested in the investigation, and has since made two appropriations of $5,000 for prosecuting the work. The coöperation of The American Museum of Natural History, The New York Botanical Garden, scientific departments of Columbia University and other institutions was secured, and both field-work and the study of the collections made has progressed almost continuously. The cooperating institutions already had some collections from Porto Rico. The two agricultural experiment stations of Porto Rico, one at Mayaguez and one at Rio Piedras, have also aided the investigation. A number of preliminary papers dealing with special phases of the work have been published. The publication of the final reports of the survey is herewith commenced and will be continued in the following sequence: geology, paleontology, botany, zoölogy and anthropology.

Professor Crampton proceeded to Porto Rico at the end of 1913 and carried out a zoölogical reconnaissance, traveling over a large part of the island, and discussed the plan with officials of the Insular Government. He subsequently published an account of Porto Rico.[1]

In January, February and March, 1914, Dr. J. A. Shafer prosecuted botanical exploration on the island Vieques, one of the small islands politically a part of Porto Rico, and made the first representative collection of plants obtained on that island.[2]

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[1] Am. Mus. Jour., XVI, pp. 59-70.

During February and part of March, 1914, Dr. Britton, accompanied by Mrs. Britton, Mr. John F. Cowell and Dr. Frank E. Lutz, made botanical and entomological collections in the northern and western parts of Porto Rico and in the small islands Desecheo and Mona, which yielded several thousand specimens and much information. Dr. Britton contributed to the twenty-fifth anniversary celebration of the Missouri Botanical Garden a paper on The Vegetation of Mona Island.[3]

In the summer and autumn of 1914, zoölogical collections were made over considerable portions of the island by Messrs. Roy W. Miner in marine invertebrates and myriopods, John T. Nichols in fishes, and Frank E. Watson and H. G. Barber in insects and arachnoids. Many thousand specimens were obtained and important additions were made to the knowledge of these groups of animals. The spiders of this collection, taken with those previously obtained by Professor Crampton and Dr. Lutz, yielded important information, which was utilized by Dr. Lutz in his List of Greater Antillean Spiders, with Notes on Their Distribution.[4] Nichols has published some of the results of his work under the title Fishes New to Porto Rico.[5]

The geological investigation was commenced by Dr. Charles P. Berkey and Dr. Clarence N. Fenner, who spent parts of August and September, 1914, in a reconnaissance and laid a substantial foundation for subsequent studies. Professor Berkey has published an illustrated account of this reconnaissance under the title Geological Reconnaissance of Porto Rico.[6]

In July and August, 1914, Dr. J. A. Shafer devoted about six weeks to the study of the forests of the Sierra de Naguabo, and added a number of species of plants to the known flora of Porto Rico.[7]

Under the auspices of the New York Botanical Garden, Professor N. Wille, Director of the Botanical Garden at Christiania, Norway, spent the period from the latter part of December, 1914, until the end of March, 1915, in collecting and studying the fresh-water and aerial algæ over considerable areas of the island. He obtained many thousand specimens of these organisms, which proved to be more abundant there than had hitherto been supposed. This collection has not yet been critically studied, but Professor Wille is confident that it contains some undescribed genera and numerous undescribed species. Since his return to Norway, subsequent to the expedition, Professor Wille has been much occupied with administrative duties, but it is hoped that he will yet find time to enumerate and describe the elements of this rich collection, the first comprehensive one that has been made of these minute algæ within the American tropics. He has published a narrative report of his fieldwork.[8]

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[2] Jour. N. Y. Bot. Gard., XIV, pp. 103-105.

[3] Ann. Mo. Bot. Gard., II, pp. 33-58, Pls. I, II. (Contributions from N. Y. Bot. Gard., No. 175.)

[4] Ann. N. Y. Acad. Sci., XXVI, pp. 71-148.

[5] Bull. Am. Mus. Nat. Hist., XXXIV, pp. 141-146.

[6] Ann. N. Y. Acad. Sci., XXVI, pp. 1-70. (Contributions from Dept. of Geology, Columbia Univ., Vol. XXV, No. 20.)

[7] Jour. N. Y. Bot. Gard., XVI, pp. 33-35.

The greater portions of the months of February and March, 1915, were spent by Dr. Britton, Mrs. Britton, Mr. John F. Cowell and Mr. Stewardson Brown in continuing botanical exploration, especially in western and southwestern portions of Porto Rico, including a study of the coasts from Mayaguez south to Morrillos de Cabo Rojo and westward to Ponce and Cayo Muertos. Large collections were obtained, which added much to the knowledge of the geographical distribution of the flora, and a series of rock specimens were collected and turned over to the geologists of the survey for examination.[9]

Based on the observations made on this and preceding trips, Dr. Britton outlined a plan of forest policy for the Porto Rican Government, which he presented at the spring meeting of the National Academy of Sciences, held at Washington in April, 1915, and it was transmitted to the Governor of Porto Rico. The reforestation of Porto Rico is acutely necessary. A recent report on the forests of Porto Rico by Mr. Louis S. Murphy, Forest Examiner of the United States Forest Service, is of great value in this connection.[10]

Dr. Chester A. Reeds and Mr. Prentice B. Hill devoted the months of June and July, 1915, to paleontological studies and collections in the western part of the island, obtaining over 10,000 specimens rich in fossil corals and fossil mollusks. They detected a stratum containing large quantities of fossil leaves; this noteworthy discovery, supplemented by further collections subsequently made by Mr. Bela Hubbard, gives us the first knowledge of the Tertiary flora of the West Indies. The collections of fossil plants made by Messrs. Reeds and Hubbard are being studied by Dr. Arthur Hollick. Dr. Reeds has published three maps. He discovered remains of a new fossil Sirenian, which has been described by Dr. W. D. Matthew.[11]

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[8] Jour. N. Y. Bot. Gard., XVI, pp. 132-146.

[9] Jour. N. Y. Bot. Gard., XVI, pp. 103-112.

[10] Bull. U. S. Dept. Agric., 1916, No. 354, p. 99.

[11] Ann. N. Y. Acad. Sci., XXVII, pp. 23-29.

Mr. Edwin T. Hodge spent the summer and early autumn of 1915, first, in an investigation of the supposed petroleum oil shales in the western part of the island, obtaining samples from 26 different localities, and later in the year submitted a report upon them, which gave negative results, Mr. Hodge concluding that oil-carrying shales do not exist in Porto Rico. Mr. Hodge subsequently made a detailed geological study of the Coamo region, and his results have been made ready for publication. He also made a study of the thermal springs of the island, especially those of Baños de Coamo.

Mr. D. R. Semmes prosecuted geological investigations of the section of the north central portion of the island, which, taken with the work of Mr. Hodge to the south, furnishes data for a complete geological cross-section from coast to coast. The studies of Mr. Semmes are published herewith.

Mycological studies and collections were made from June to August, 1915, by Professor F. L. Stevens, in continuation of similar investigations prosecuted by him while Dean of the College of Agriculture at Mayaguez. He visited nearly all parts of the island and collected many thousand specimens; his trip was under the auspices of the University of Illinois and of the New York Botanical Garden.[12] Professor Stevens described and illustrated the species of the large genus *Meliola* as represented in Porto Rico, under the title The Genus *Meliola* in Porto Rico, which includes descriptions of sixty-two new species and varieties.[13]

Professor Crampton continued zoölogical field-work during January, 1915, especially in the northwestern portion of the island, at which time he supplemented previous collections by obtaining large numbers of specimens in the various groups of invertebrates.

In the spring and early summer of 1915, Dr. Frank E. Lutz and Mr. A. J. Mutchler made extensive entomological collections in various parts of the island, adding some 15,000 specimens of insects and large numbers of spiders to collections previously made. Mr. Roy W. Miner and Mr. H. Mueller spent several weeks in the summer in the study and collection of marine invertebrates, especially in the vicinity of Guanica, some 8,000 specimens being obtained at that time from this region. Professor Raymond C. Osburn carried on studies of the organisms of the deeper waters in the vicinity of Guanica during the summer, obtaining over 2,000 specimens, principally by dredging.

Professor Franz Boas prosecuted anthropological and archæological investigations at several points during May and June, 1915, aided by Dr.

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[12] Jour. N. Y. Bot. Gard., XVII, pp. 82-85.

[13] Illinois Biological Monographs II, No. 4, pp. 1-86, Pls. I-V.

H. K. Haeberlin, Dr. J. Alden Mason and Mr. Robert T. Aitken. Professor Boas obtained data which caused him to doubt the general assumption that children reach maturity earlier in tropical regions than in the temperate zone, and other data which are important as regards the hygiene of childhood in the tropics. His observations on the teeth of Porto Rican children have been published by Mr. Leslie Spier.[14] He obtained cordial coöperation in this investigation from the Department of Public Education of the island. He also concluded from his observations at this time that the Porto Rican race has been influenced in its development by environment.

Professor Boas referred the collection of folk-lore data to Dr. J. Alden Mason, who prosecuted this study from June, 1915, until 1916, and accumulated an immense collection of folk tales, riddles, ballads and songs, which was subsequently referred for editing to Professor Aurelio M. Espinosa, of Leland Stanford University, whose work on this important contribution is now approaching completion, and who has reported to the Committee that the documents are the most important contribution of its kind made to literature. Professor Espinosa and Dr. Mason have published Porto Rico Folk Lore—1. Riddles.[15]

Dr. Haeberlin made excavations in the Jobo district, including that of one stone enclosure and a cave, which contained ceremonial objects and large numbers of bones of an extinct mammal. A large cave in the vicinity of Utuado, excavated by Messrs. Mason and Aitken, proved to be the burial ground of an ancient community, and here also large numbers of bones of an extinct mammal were found.[16] One of these mammals proved to be new to science, and has been described by Dr. J. A. Allen under the title An Extinct Octodont from the Island of Porto Rico, West Indies.[17] Dr. Haeberlin has published a paper entitled Some Archæological Work in Porto Rico.[18]

An ancient village site at Capá, located by Professor Boas and subsequently investigated by Messrs. Mason and Aitken, proved to be the most important of all archæological localities thus far discovered in Porto Rico. Efforts were made by the Committee to induce the Porto Rico Government to purchase and preserve this site as a national monument, but hitherto without success. A preliminary description of the site has been given by Dr. Mason.[19]

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[14] Am. Anthropologist, XX, pp. 37-48.
[15] Jour. Am. Folk-Lore, XXIX, pp. 423-504.
[16] XIX Congress of Americanists, pp. 224-228.
[17] Ann. N. Y. Acad. Sci., XXVII, pp. 17-22, Pls. I-V.
[18] Am. Anthropologist, XIX, pp. 214-238.
[19] XIX Congress of Americanists, pp. 220-223.

Dr. Marshall A. Howe spent parts of June and July, 1915, in continuation of his previous studies of marine algæ, principally along the southwestern coast from Ponce and Cayo Muertos to Cabo Rojo. During this trip he obtained about 3,000 specimens, including some species additional to the known flora of the island.[20]

Professor Bruce Fink, of Miami University, proceeded to Porto Rico in November, 1915, and spent part of the winter there in making extensive collections of fungi and lichens. He has generously contributed information obtained by him to the Committee.

Dr. Herbert J. Spinden prosecuted archæological work at several points during the spring and summer of 1916 and made extensive collections, the study of which yielded interesting and valuable information. He excavated certain shell heaps and obtained specimens and information therefrom, which he regarded as throwing light upon the origin of Porto Rican aborigines. He also studied the aboriginal petroglyphs or rock-carvings.

Mr. Bela Hubbard carried out a geological survey of the northwestern section of the island in the summer of 1916, and his description of this work is in process of completion for publication. Dr. Charles R. Fettke studied the southwestern districts of the island in an areal geological survey, which included a detailed study of the extensive areas of eruptive rocks. The study of the large collections made by him is progressing.

Mr. A. K. Lobeck studied, during the latter part of 1916 and January, 1917, the physiography of the entire island, and the results of this investigation are prepared for publication.

During the summer of 1916, a very important study of the parasitic fungi of Porto Rico was made by Professor H. H. Whetzel, of Cornell University, and Dr. E. W. Olive, of the Brooklyn Botanic Garden, aided by a grant from the New York Botanical Garden, and several thousand specimens of these plants were obtained, which are under investigation by a number of different experts.

Mr. H. E. Anthony prosecuted studies of recent and fossil mammals in Porto Rico during the summer of 1916, and made some highly interesting and important discoveries, which have been described by him in three illustrated papers:

Preliminary Report of Fossil Mammals from Porto Rico.[21]

Preliminary Diagnosis of an Apparently New Family of Insectivores.[22]

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[20] Jour. N. Y. Bot. Gard., XVI, pp. 219-225.

[21] Ann. N. Y. Acad. Sci., XXVII, pp. 193-203.

[22] Bull. Am. Mus. Nat. Hist., XXXV, pp. 725-728.

New Fossil Rodents from Porto Rico, with Additional Notes on *Elasmodontomys obliquus* Anthony and *Heteropsomys insulans* Anthony.[23]

During the progress of the survey, Dr. John A. Stevenson, of the Insular Experiment Station at Rio Piedras, has made botanical collections in various parts of the island, which have contributed much to our knowledge of the flora; he is now preparing a list of the fungi of Porto Rico. Dr. Basil Hicks Dutcher, U. S. A., stationed at San Juan, has given valuable aid to nearly all our field parties by advice, information and personal assistance.

A number of reports of progress and other presentations of parts of the work have been made at meetings of the Academy from time to time. An outline of the proposed survey was presented by members of the Committee in the form of a symposium at the meeting of April 13, 1914.[24] Another symposium was given at the meeting of December 14, 1914.[25] At the meeting of the Section of Geology and Mineralogy on November 1, 1915, preliminary reports on field-work were given by Messrs. Semmes, Hodge and Reeds.[26] At the meeting of the Section of Biology November 8, 1915, communications were presented by Messrs. Reeds, J. A. Allen and Matthew.[27] The Committee submitted a report of progress at the annual meeting of December 20, 1915.[28]

At the meeting of the Academy held January 24, 1916, Dr. Boas, Mr. Aitken and Dr. Haeberlin[29] presented communications on ethnology and archæology, and at the meeting of May 15, 1916, geological communications were presented by Messrs. Hodge, Semmes, Reeds, Fettke, Hubbard,[30] Lobeck and Professor Berkey.[31]

During several months of 1917, Mr. Graham J. Mitchell prosecuted an areal geological survey of the southwestern portion of Porto Rico, and his report of this work is in progress of preparation for publication. Dr. Charles R. Fettke has recently published, with the approval of the Committee, a paper entitled The Limonite Deposits of Mayaguez Mesa, Porto Rico.[32]

The final geological reports are being written, for the most part, by the several geologists who have participated in the field-work, and, as already stated, considerable portions of them are ready for publication. Dr. T. W. Vaughan, of the United States Geological Survey, has kindly consented to study the collections and prepare the descriptions of the fossil corals, and those obtained up to the present time have already been sent to him.

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[23] Bull. Am. Mus. Nat. Hist., XXXVII, pp. 183-189.
[24] Ann. N. Y. Acad. Sci., XXIV, pp. 369.
[25] Ann. N. Y. Acad. Sci., XXIV, pp. 398, 399.
[26] Ann. N. Y. Acad. Sci., XXVI, pp. 433-436.
[27] Ann. N. Y. Acad. Sci., XXVI, pp. 436-439.
[28] Ann. N. Y. Acad. Sci., XXVI, pp. 456-462.
[29] Ann. N. Y. Acad. Sci., XXVII, pp. 250, 251.
[30] Bull. Am. Inst. Mining Engineers, No. 135.
[31] Ann. N. Y. Acad. Sci., XXVII, pp. 277-282.
[32] Bull. Am. Inst. Mining Engineers, No. 135, pp. 661-676.

The final botanical reports are being prepared by the following investigators:

Flowering Plants.—Dr. N. L. Britton and Mr. Percy Wilson, the grasses by Professor A. S. Hitchcock.

Ferns and Fern Allies.—Preliminary work by Miss Margaret Slosson.

Mosses.—Mrs. N. L. Britton and Mr. R. S. Williams.

Hepatics.—Professor A. W. Evans.

Lichens.—Professor Lincoln W. Riddle.

Fungi.—Dr. W. A. Murrill, Dr. F. J. Seaver, Professor J. C. Arthur, Professor F. L. Stevens, Professor H. H. Whetzel, Dr. E. W. Olive, Dr. John A. Stevenson.

Algæ (marine).—Dr. Marshall A. Howe.

Algæ (fresh-water and aerial).—Professor N. Wille.

No arrangement has yet been made for the study of Porto Rican diatoms.

The zoölogical collections are being studied and final reports prepared as follows:

Mammals.—Mr. H. E. Anthony.[33]

Birds.—Mr. Alex. Wetmore has published an exhaustive report on the birds which may be taken as a basis for our document.[34]

Reptiles.—Preliminary work by Miss M. C. Dickerson.

Amphibians.—Preliminary work by Miss M. C. Dickerson.

Fishes.—Mr. J. T. Nichols and Professor C. F. Silvester.

Insects:

- Orthoptera.—Mr. J. A. G. Rehn and Mr. Morgan Hebbard.
- Coleoptera.—Mr. C. W. Leng and Mr. A. J. Mutchler.
- Hemiptera.—Mr. H. G. Barber.
- Lepidoptera.—Mr. F. E. Watson.
- Hymenoptera.—Mr. J. Bequaert and Dr. F. E. Lutz.

Myriopods.—Mr. Roy W. Miner.

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[33] Mem. Am. Mus. Nat. Hist., N. S., II, Part 2.

[34] Bull. U. S. Dept. Agric., 1916, No. 326, p. 140.

Mollusks.—Preliminary work by Dr. L. P. Gratacap.
Ascidians.—Dr. Willard Van Name.
Crustaceans.—Mr. Roy W. Miner and Dr. Willard Van Name.
Annelides.—Professor A. E. Treadwell.
Echinoderms.—Preliminary work by Mr. D. M. Fisk.
Bryozoans.—Dr. R. C. Osburn.
Coelenterates.—Mr. Roy W. Miner.

Representative collections of Porto Rican protozoans have not yet been made.

The anthropological and archæological documents are being written by the several investigators who have conducted the field-work. Preliminary papers, in addition to those already noted in this report, are being prepared by Professor Boas on anthropometrical observations in Porto Rico, by Dr. Mason on the archæological investigation of the very important site at Capá, by Dr. Aitken on the cave sites near Utuado, and by Dr. Mason and Professor Espinosa on Porto Rican folk tales.

As to the general progress of the survey, it may be stated that over two-thirds of the necessary geological field-work has been completed. Except for an investigation of the diatoms, which has not yet been arranged for, no additional botanical field-work is really essential, although the final reports would be more complete if additional collections were made, but this is of course true all over the world. Considerable additional zoölogical field-work and additional collections in several of the groups of animals are highly desirable, and, as before remarked, the protozoa have not been collected. Anthropology and archæology still offer widely attractive fields for further examination. No oceanographic work has as yet been possible.

In cooperation with the Insular Government, portions of the collections made have been returned to Porto Rico to form the basis of a Natural History Museum, and other portions will be forwarded to Porto Rico as the study proceeds. The remainder is to be divided among the coöperating institutions and investigators.

The islands St. Thomas, St. Jan and St. Croix, recently purchased by the United States from Denmark, lie close to Porto Rico, to the east and southeast. It is highly desirable, before our survey is brought to a close, that these should be studied geologically, zoölogically and archæologically. Their botany is fairly well known. I have recently contributed a catalogue of their known flora to the Brooklyn Botanic Garden, and this has been published in the volume of papers presented on the occasion of the opening of the new laboratories of that institution.[35] The survey will thus be made to include all the Caribbean insular possessions of the United States as they stand at present, and be entitled A Scientific Survey of Porto Rico and the Virgin Islands.

The Chairman of the Committee gratefully acknowledges aid from the other members in the preparation of this historical sketch of the survey.

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[35] Mem. Brooklyn Bot. Gard., I. pp. 19-118. (Contributions from N. Y. Bot. Gard., No. 203.)

INTRODUCTION TO THE GEOLOGY OF PORTO RICO

By Charles P. Berkey

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INTRODUCTORY STATEMENT

The Island of Porto Rico lies between latitude 170° 54′ and 18° 30′ north and longitude 65° 13′ and 67° 15′ west. It is the most eastern and southern of the Greater Antilles. Thus it lies within the trade-wind belt, which is an important factor in the local variations of its tropical climate.

In the Atlantic immediately north of Porto Rico lies Brownson Deep, which reaches the profound depth of 24,000 feet, and in the Caribbean farther to the south lies Tanner Deep, reaching 15,000 feet. Although its loftiest mountains do not exceed 4000 feet elevation above the sea level, the whole island appears to be just a portion or segment of a great mountainous mass or chain that rises from a submerged platform above which its true relief might well be measured. A relief difference of 28,000 feet such as is given from the bottom of Brownson Deep to the top of El Yunque is not exceeded in many places the world over within such moderate distances, but it must not be assumed that this is the elevation above the submarine platform.

Porto Rico may thus be regarded to some advantage in the present consideration as a badly eroded uppermost portion of a great mountain mass which probably at one time formed a part of a chain with general east-west trend, most of which is now submerged. Certain very elevated segments of this chain still stand above sea level and form the islands of the Greater Antilles. Whether or not the structural relations of these exposed segments are of fault-block type and what relation such an island as Porto Rico may have to a former continental mass extending toward and possibly connecting North and South America, however interesting or suggestive they may be, are questions that might be better discussed in the summary at the conclusion of this survey rather than in this preliminary statement. Such questions are involved in the final solution of the geologic history of the island, on which a whole projected series of district and special studies have a bearing.

Porto Rico is very mountainous. A central cordillera extends nearly east and west, starting abruptly at the sea near Rincon on the west coast and continuing to El Yunque, the great mountain summit which forms the central feature of the eastern end of the island. It is not by any means as simple, however, as this statement would suggest, for there are branches of the main range both east and west, but especially to the east, where the Sierra de Luquillo, culminating in El Yunque, and the Sierra de Cayay, 10 miles farther south, form very distinct features. At either end of the island the chief mountain relief is centrally located, but throughout the whole of the middle portion and for two-thirds of the total length of the island, including the Sierra de Cayay, and thence westward for 60 miles, the chief mountain range lies only about 10 miles from the south coast. Almost two-thirds of the total area, therefore, belongs to the northerly slopes of the chief mountain range.

Although the topography on the whole is very rugged and the island has a decidedly mountainous aspect, there is almost everywhere a very moderate relief along the coast and at many places the coastal lands are almost flat. These very flat areas lie always at the mouths of rivers and undoubtedly have been made in large part by deposition of the silts of the streams. Such alluvial tracts are called playas in Porto Rico.

All relief forms except these playas are of erosional origin. Exceedingly steep slopes are the rule, suggesting early maturity in physiographic history. This phase of the geologic history of Porto Rico has been made the subject of a special study by Mr. Armin K. Lobeck and will soon be published in this series. One of the most surprising things is the way the soils cling to these steep hillsides, and it is possible to repeatedly see slopes under cultivation that measure from 30 to 40 degrees.

Numerous small islands lie along the coast. Two of comparatively large size, Vieques and Culebra, which are respectively 20 and 7 miles in length, mark the continuation of the Porto Rican land mass toward the east. All are included as a part of the studies of Porto Rico.

Streams are numerous and surprisingly large. Mr. H. M. Wilson (1899, 1900) has published an excellent account of the hydrology of the island, and to this reference should be made for details of this nature. He credits this small island with 39 large and 1300 small streams.

Rainfall is very unevenly distributed. At the east end, near El Yunque, there is an annual rainfall of 123 inches. On the other hand, at Cabo Rojo, at the extreme southwest corner, there is seldom any rain at all. Because of the high mountain ranges, there is an abundance of rain on the windward side, which includes the east end and most of the north side of the island, and since the principal range stands far south of the middle, the larger portion of the island is fairly well watered. A comparatively narrow strip along the south side, especially to the west from Guayama, and again a strip at the northwest corner, are comparatively arid. Extensive irrigation works have been constructed along the south side.

In most districts the bed rock is compact enough to discourage underground circulation and the run-off is correspondingly responsive to rainfall. But in the northwest corner of the island, on a broad limestone belt reaching from Aguadilla to Camuy, and less prominently even farther eastward, there are many caves and sinks, and a most remarkable minor topography,[1] where underground water circulation is locally of much importance. In some cases large streams rising on other ground farther inland are completely lost here for long distances, following subterranean channels in these limestones.

There are no inland lakes and but few coastal lakes. All of these appear to be related either to playa development or to comparatively recent elevation and subsidence. One near Guanica still retains internal evidences of its former marine relations.

The climate is strictly tropical, but it is so tempered by reason of the trade-wind breezes and by the mountainous aspect and elevation of much of the country that it is usually very agreeable indeed. The entire lack of great changes of temperature and the prevailingly moist conditions over most of the island have a direct influence on the character of rock decay and disintegration and also on the quality of the soil.

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[1] For discussion of this feature in much more detail, see the following article by Douglas R. Semmes on The Geology of the San Juan District, Porto Rico.

The average daily temperature is 80 degrees, and it rarely rises above 90 or drops below 70, while the maximum is said to be 99 degrees.

In area Porto Rico covers 3,670 square miles, and is therefore about three-fourths the size of the State of Connecticut. It is roughly rectangular in outline, with the longer axis east and west, and in actual dimensions is approximately 35 miles in average width and 105 miles long.

It is the fourth in size of the West India Islands. Porto Rico is very productive and is said to be the most densely populated country in the world.

GEOLOGICAL RECONNAISSANCE

The Island of Porto Rico has never had a systematic survey, and comparatively few articles have been written on its geology. A few papers, however, have described certain special features and general physical conditions in a very instructive way. The writings of R. T. Hill (1898, 1899), especially, contain a comprehensive outline of the geologic history of the Island of Porto Rico, and those of H. M. Wilson (1899, 1900) and W. Dinwiddie (1899) give as good general description of its physical features as is anywhere to be found.

In the summer of 1914 the writer, in company with Dr. Clarence N. Fenner of the Geophysical Laboratory, Washington, made a geological reconnaissance of the island, with the object of determining the chief lines of its geologic history and outlining the major problems to receive further study. This reconnaissance was undertaken as a part of the Natural History Survey planned by the New York Academy of Sciences and was intended to lay the foundations of a complete geological survey which it was expected would become the work of several subsequent expeditions and might extend over 4 or 5 years. Observations made at that time, together with additional studies of material secured on this first expedition, served as the basis of a report entitled Geological Reconnaissance of Porto Rico (Berkey, 1915), which was published the following year, and has been the guide for several special expeditions and district studies since that time. This paper still constitutes the fullest statement of the structure and origin and geological history of the whole island; but it has now been supplemented by several district studies which have been made in much greater local detail, and also by a special investigation of the physiography of the island; all of which, with yet others to be made, form a part of the plan for this Survey.[2] Seven such districts and areal studies and four general investigations were originally planned. Five of the district or areal studies have been made and one general investigation has been completed.

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[2] A detailed list of these topics and studies is given at the end of this article.

MAJOR GEOLOGIC FEATURES

Determination of the principal rock types and larger structural units, together with their relations and the principal problems deserving further investigation, may be considered the chief work of a general geologic reconnaissance. To this task the energies of the first expedition was directed with sufficient success, as it now appears with respect to its major lines, to stand the test of the more detailed subsequent work. A brief outline of the more important geologic features characterizing the whole island follows.

Rock Formations

There is an exceedingly large number of formational rock units in this field and a very great number also of rock types or varieties, and the confusion as a consequence is so great, at first sight, that it all appears a hopeless muddle. This is especially true of the interior of the Island rather than the coastal margins. In the higher interior regions igneous rocks and clastics derived more or less directly from igneous action such as tuffs and ashes prevail, although formations of simpler sedimentary (water laid) habit are very abundant and sedimentation structures are at least as prominent as are the massive structures of the true igneous rocks.

Along the coastal margin, on the other hand, especially along the north coast west of San Juan and along the south coast west of Juana Diaz, the rock formations are much simpler in aspect. Soon one comes to realize, therefore, that two distinct formational series are represented and, judging from the very marked differences in habit, one would expect them to be separated by a more or less profound break or unconformity.

To this extent at least the first suggestion in an attempt to organize the complex structure of the island is correct. There are undoubtedly two very distinct formational series which, on more extended inspection, prove to be readily distinguished and separated. The one referred to as characterizing the interior is much the more complex in make-up and structure and most of its members have been extensively deformed and modified since their deposition. The simpler series is made up of a succession of sedimentary and organic accumulations, including shales, marls, chalks and limestones, little disturbed. As should be expected, there is a very distinct unconformity between these two major series represented by an erosion plane which bevels the upturned members of the older complex and seems to have all of the earmarks of a peneplain. The complexity of the older of these two series suggests again the possibility of a subdivision of it, but all studies so far have failed to show a major line of separation. The formational groupings are therefore in approximately the order suggested in their original reconnaissance, essentially as follows:

THE YOUNGER SERIES

This includes shale and limestone beds, reef limestones and occasional sandstone and pebble accumulations. These are readily recognized as belonging to the Tertiary period, but the greater detail of age relation is a matter necessarily left for the more elaborate studies of those districts where these formations are prominent or to the results of general stratigraphic and paleontologic study.

The Younger Series as used in these studies includes at least two very readily differentiated but very unevenly developed members which were referred to in the reconnaissance under names taken from their most typical occurrence.

(*a*) The *San Juan Formation* is the most recent consolidated representative in the island. It is confined to the immediate coast margins, especially the north coast, and the adjacent small islands, the most striking occurrence forming the promontory on which the city of San Juan is built.

(*b*) The *Arecibo Formation* is a thick series of limestones, marls and shales. This is a much more extensive and geologically important member than the San Juan. Subdivision is doubtless possible with further study, and it has been convenient from the very first to distinguish certain particular facies or the beds of particular localities by special locality names; but these do not necessarily represent subdivisions of wide applicability. They have been, however, of distinct usefulness in all studies thus far made. The most commonly used are the following:

1. The *Arecibo limestone*
   upper limestone member on the north side of the island.
2. The *San Sebastian shales*
   lower, shale member on the north side of the island.
3. The *Juana Diaz marls*
   south side shales and marls near Juana Diaz.
4. The *Ponce Chalk beds*
   very white chalks near Ponce on south side of the island.

The greater part of all these beds are satisfactorily determined to be of Oligocene age, but the latest studies indicate the presence of representatives of both Eocene and Miocene age as well.

THE OLDER SERIES

This includes a complex association of tuffs, ashes, shale, conglomerate, limestones and a very great variety of intrusives and occasional lava flows. These are readily seen to be enough older than the other series to have suffered much additional modification of petrographic character and deformation, and it is comparatively simple also to determine that the members of the series as far as they bear fossil evidence seem to be confined to late Mesozoic age, perhaps wholly to the Cretaceous period.

The Older Series thus far has failed to show even as distinct lines of subdivision as the Younger. Perhaps there are breaks as great as that between the San Juan and the Arecibo formations of the Younger Series, but the structures are much more obscure, by reason of deformation and other changes, and are less fully exposed. There is a suggestion of a possible structural break marked by one belt of limestones found by Dr. Semmes in the San Juan district (see San Juan District geologic map) and perhaps in the La Muda Limestone of the original reconnaissance account, but no other supporting evidence is yet at hand, even after a study of more than half of the island in detail.

The Older Series is apparently a fairly continuous accumulation of no greater complexity and structural difficulty than should be expected from a long and almost continuous volcanic history.

Although still regarded as a single series of formations, it has been found very convenient in this case also to designate certain well marked units by locality names. No assumption is made as to their extent or the possibility deserving recognition in attempts at correlation. The Reconnaissance expedition made free use of such terms to much advantage in the field, and later still others have been used by the investigators of special districts. As a matter of fact, the great difficulty found in the beginning in following any single field unit very far or identifying it at other places made the use of many locality and arbitrary names particularly serviceable at that time. Subsequent studies have not successfully eliminated them, and it may well be that the accumulating proof of the great variability of all these formations as well as other units will compel the retention of such local names. Among the terms that belong to the reconnaissance stage and that bid fair to be retained are the following:

1. The Fajardo shales, a very widespread type of blocky shale.
2. The Mayaguez shales, similar to Fajardo shales in general structural habit.
3. The Coamo Tuff-Limestone, a heavy limestone carrying abundant tuff fragments.
4. The Trujillo Alta Limestone, a very limited occurrence of dense limestone.
5. The "Shred" Limestone, a name suggested by the appearance of the chief fossil form.
6. The La Muda Limestone, a formation that seems to mark a break of more than average consequence.
7. The Mountain Limestone, of Hill—thin-bedded, shaly limestones and limy shales of very extensive development along some of the mountain ridges.
8. The Corozal Limestone, a peculiar local occurrence of limestone breccia at Corozal.

PETROGRAPHIC RANGE

The petrographic variety of this older series is very great, but the types of large consequence are not numerous. They may nearly all be included within such group terms as limestone, marls, shales, sandstones, conglomerates, tuffs, ashy tuffs, ashes, and ash shales among the organic sedimentary, and clastic rocks; andesites, andesitic porphyries, diorite, syenite and granite as the chief crystalline igneous rocks; and serpentines and graywackes and rarely some contact products as the chief badly modified types.

Although the range of different types when stated in this form is not at all remarkable, there is almost every conceivable variation of minor composition, quality, structural or textural peculiarity, physical condition, degree of modification and state of preservation represented in each one.

Most of them, furthermore, occur in an almost countless succession of beds and sills or other field units of all sizes from masses of many square miles in areal extent or hundreds of feet in thickness to thin layers or stringers or dikes of only a few inches. As a matter of fact, the most striking thing about these occurrences is the exceedingly great number of small units which alternate or change so many times in short distances that detailed mapping of them, or even an attempt to represent this detail by the most carefully constructed geologic cross-sections, seems hopeless. All practicable representations of the geologic structure are necessarily generalizations.

Maps of any kind covering portions of districts must be done on the basis of a grouping together of great numbers of individual units in recognition of the domination of some particular type. Thus it seems to be possible to mark out belts or areas of dominant limestones, shales, tuffs or conglomerates, some of which are fairly satisfactory as a basis for a geological map. But even in some of these cases the smaller individual constituent units vary so rapidly along their strike that the average quality is wholly different within distances of a few miles. This character makes detailed geologic mapping a difficult and most discouraging undertaking.

The Younger Series, on the other hand, is very much simpler, since no igneous rocks are represented at all. But even here, within the limits set by the shales and sands of one extreme and the marls, chalks, reefs and massive limestones at the other, there is every gradation, the character being evidently under the control of such local conditions, and so poorly marked off in succession by fundamental differences, that here again a subdivision for mapping purposes is extremely difficult to apply. A strictly paleontologic subdivision, however, is being more successfully applied as the investigation of certain districts proceeds.

STRUCTURE

The general geologic structure of the Younger Series of formations is simple. The beds lie, for the most part, dipping gently toward the sea. This is especially true of the broad belt of these rocks forming the north side of the island. On the south side there is some deformation, chiefly due to faulting and crowding. In many places also there is slumping due to sink-hole development.

The Older Series has, on the contrary, a very complex structure. Only rarely do the bedded rocks have their original attitude. They commonly stand much tilted and even vertical, or in rare cases overturned, and faulting is common. But the most prominent structural feature is the association literally of multitudes of thin-bedded ashy or limy shales and equally thin igneous intrusive sheets or sills. It is not at all rare to see an alternating series of such units, a few inches or a few feet thick, so regular that when well weathered the whole succession looks simply like a series of alternating shaly and more massive beds. The number and complexity of the igneous intrusions are surprisingly great and at many places the intrusive members dominate in the formation. In most cases there are no noticeable contact effects.

Much larger intrusive sills, which are almost always dioritic in composition, are also very common and there are a few large bosses several miles across of granite, syenite and serpentine. In a few places the local interruption of the beds by massive tuffs cut by intrusive complexes seems to mark old volcanic vents which must have been active after the adjacent strata had formed and perhaps had attained something of the quality and attitude that they now have. One large old vent of this kind is now the site of the Jacaguas Reservoir. The occurrence of beds of limestone breccia, including great amounts of tuff fragments, and a continuation of the same regular beds beyond such complexes, are further supports to this interpretation.

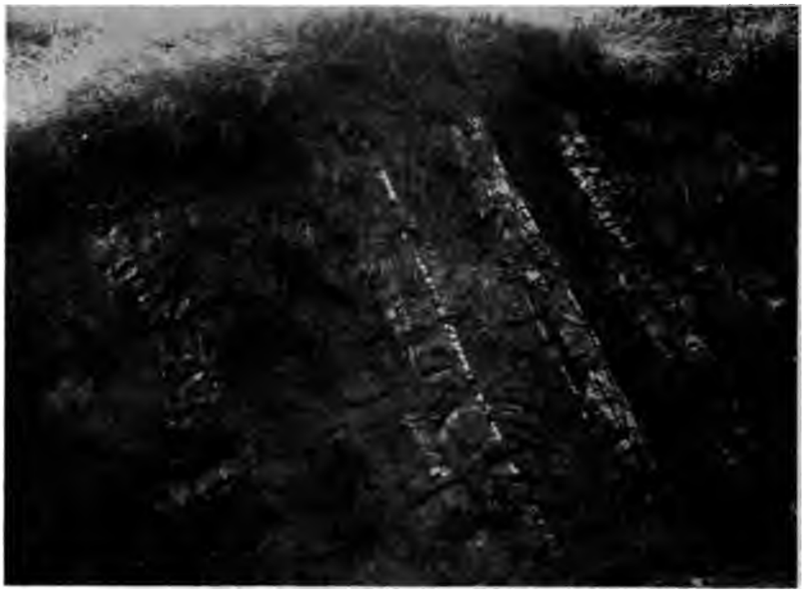

FIG. 1.—*Diorite porphyry sills*

These sills are intruded between layers of calcareous shales and ash beds on the road near Comerio. The streaked or banded layers are shales, the massive portions, seen best at the left side of the print, are sills. A transgressive relation can be seen between the two layers at the extreme left.

Minor structural features such as xenolithic inclusions in the intrusives are extensively developed. Sometimes a sill or dike is literally crowded with tuff fragments so closely packed together that the whole has more the general outward appearance of a tuff than a bona fide intrusive. Repeated inspection of the structure, however, has removed every doubt as to the essential correctness of the observation. A rather remarkable minor structure in the San Juan formation, which is believed to be a consolidated dune sand, is illustrated in the accompanying figure. It

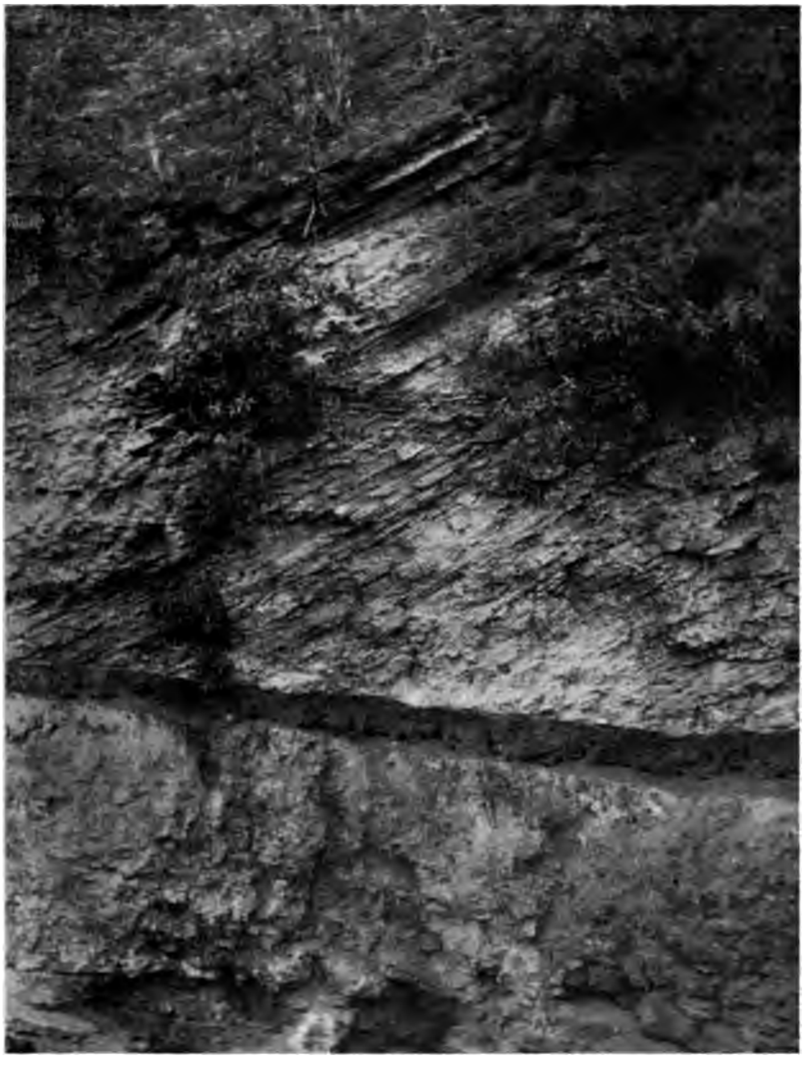

FIG. 2.—*Detail of the double structure in the San Juan formation at Arecibo*

This photograph was taken to bring out the horizontal structure crossing the inclined layers. There is no doubt whatever that the dark layer of less consolidated sand in the lower third of the photograph is a primary bedding structure, but the horizontal marks crossing the inclined layers in the upper part of the view are believed to be of secondary origin.

shows nearly horizontal bedding at the base, with highly inclined thin beds (cross-bed structure) above, on which or in which a less pronounced horizontal structure is also preserved completely crossing the inclined layers. This formation has not been deformed at all, so the structures must be connected with the original sedimentation and perhaps the induration processes in some way. No better explanation has been offered than that of the Reconnaissance report, which regards the cross-bed structure as a wind-laid deposit and the horizontal structure, crossing it, as a cementation or induration structure developed in standing water during successive steps of subsidence and elevation.

FIG. 3.—*Haystack (pepino) hills*

A characteristic view, showing the small soil-covered flats and associated haystack hills found in the region of the Arecibo formation. Photograph taken on the road between Arecibo and Barceloneta.

RELIEF FEATURES

The present relief features of Porto Rico are all those of simple erosion. In the interior the structure is so complex and variable that surface forms seem to show little structural control. The mountains are rugged, steep and irregular in outline. Mountain tops are almost everywhere knife-edge divides, no matter whether they cross or follow the rock structure.

The features of the coastal margins, however, are much more influenced by formational attitude. The younger series of beds lie on the rather evenly eroded (peneplained) surface of the complex older series. Erosion has stripped back much of this younger cover from the old land, thus developing the usual inner lowland and cuesta forms with traces of the old peneplain well preserved on the adjacent ground on the inner side. A full treatment of these features is included in a physiographic study of the island which has already been made by Mr. Armin K. Lobeck, and whose report will soon be published as a part of this Survey.

On the cuesta and the outer slopes, wherever limestones are the surface rock, great numbers of caves have developed. A most striking surface feature is thus produced with sink-holes as the first distinct stage which by enlargement develop flats separated one from the other by remnants of the old walls. In some districts these last remnants form great numbers of small conical hills, referred to by Hill as the *pepino* hills and by Berkey as haystack hills. This is the most unusual and remarkable of the surface features of the island.

Immediately along the coast one may find occasional traces of a step-like form which has attracted much attention. They were taken at once to be sea terraces, and subsequent studies seem to confirm that conclusion. Such forms, therefore, indicate that the island has been elevated in comparatively recent time. Other related features, among them the occurrence of marginal islands, suggest that at one time the island may have stood even higher than now. Probably there has been a succession of elevations and subsidences in later as well as in the earlier geologic history of the island.

Geologic History

In barest outline the geologic history of Porto Rico is simple. A complete or even a reasonably full account of the geologic history of Porto Rico cannot be written at this step of the investigation.

There is no record of very ancient rocks at all. But in Cretaceous time, or perhaps immediately before, this region was the scene of violent and long-continued explosive volcanic activity which resulted through many vicissitudes in the accumulation of thousands of feet of volcanic clastic matters, partly in massive unassorted condition, partly worn, transported and assorted, partly mixed with weathered detrital matters and organic growths, all together forming a great succession of tuffs, ashes, shales and limy rocks.

The summary of the major historical items formulated in the original Reconnaissance report is still serviceable:

(1) A long geologic period of volcanic activity, accompanied by marginal attempts at assorting of fragmental and detrital material and organic accumulation disturbed from time to time by renewed or extended igneous activity.

(2) A dying out of volcanic energy, greater stability of the mass with respect to elevation and subsidence, and erosional attack continued long enough to result in extended planation and partial baseleveling with final extensive submergence.

(3) The development of an unconformable overlying series of shales, reef limestones and related deposits chiefly of organic origin, brought to an end by final re-emergence.

(4) The development of present surface features under stream erosion and marine marginal attack, with modifications arising from oscillation of level.

PROBLEMS OF THE SURVEY

The problems that were suggested in the Reconnaissance report have engaged the endeavors of several expeditions. Altogether seven have been made and four studies have been completed. Others are yet to be made. The whole plan with its accomplishments may be listed as follows:

EXPEDITIONS

(*a*) Expedition of 1914 to make a reconnaissance.

1. Dr. Charles P. Berkey and Dr. Clarence N. Fenner. Reconnaissance report (Berkey, 1915).

(*b*) Expeditions of 1915.

2. Dr. Chester A. Reeds. Study of Tertiary stratigraphy, and especially an attempt to establish the subdivisions of the Younger Series and make paleontologic collections. New base map prepared (published with this paper).
3. Mr. Douglas R. Semmes. Study of the San Juan District (Semmes, 1919).
4. Mr. Edwin T. Hodge. The Coamo-Guayama District.[3]

(*c*) Expeditions of 1916.

5. Mr. Bela Hubbard. The Aguadilla-Lares District.[4]
6. Dr. Charles R. Fettke. The Humacao District.[4]
7. Mr. Armin K. Lobeck. A general study of the physiographic history of the island.[3]

(*d*) Expedition of 1917.

8. Mr. Graham John Mitchell. The Ponce District.[4]

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[3] Report ready for publication.

[4] Report interrupted by the war.

CLASSES OF STUDIES

The whole list of studies of all kinds fall into three classes:

(*a*) General studies, covering certain features affecting the whole island.

(*b*) Areal or district studies, with accompanying geological maps.

(*c*) Special investigations on problems suggested by local conditions or the material collected.

GENERAL STUDIES

Among the general questions which have been considered to belong to the island as a whole are the following:

New Base Map.—The making of an accurate detailed map, such as might be represented by topographic sheets of the kind prepared by the U. S. Geological Survey, is an undertaking much beyond the scope and facilities of this Survey. Each investigator of a district has undertaken the correction of the maps available for his own area in enough detail for the purpose. These districts, however, are not complete to such a point that a general relief map for the island could yet be constructed from them. As a step, therefore, preliminary to that result, the data of all previously published maps, together with such notes as were available from field observation, have been compiled, under the direction of Dr. Chester A. Reeds, in the form of a new relief map which is published herewith.

Physiography of Porto Rico.—After the reconnaissance and first district studies were made, it became apparent that a general physiographic study covering the whole island would be particularly desirable. The opportunity to make a complete study of an isolated land mass, with a physiographic history probably similar to most of the West Indian islands, seemed to be particularly good. Mr. Armin K. Lobeck undertook this study and his work is completed.

Tertiary Stratigraphy.—This general problem, which was considered too broad for a district study, was recognized as a difficult investigation that deserved to be considered by itself. Dr. Chester A. Reeds entered upon the investigation by making a collecting expedition in the season of 1915. It was the intention to include in this study a determination of the principal subdivisions and boundaries of the Tertiary strata for the whole island, and it was hoped that this could be done on simple enough lines and promptly enough to be of service to all of the men doing district mapping and making local studies. The problem has been found especially difficult and final results are not yet reached. In the meantime the practical matter of mapping has been solved in each district as well as may be, and probably no full statement of the Tertiary stratigraphy will now be attempted till all of these separate studies are available.

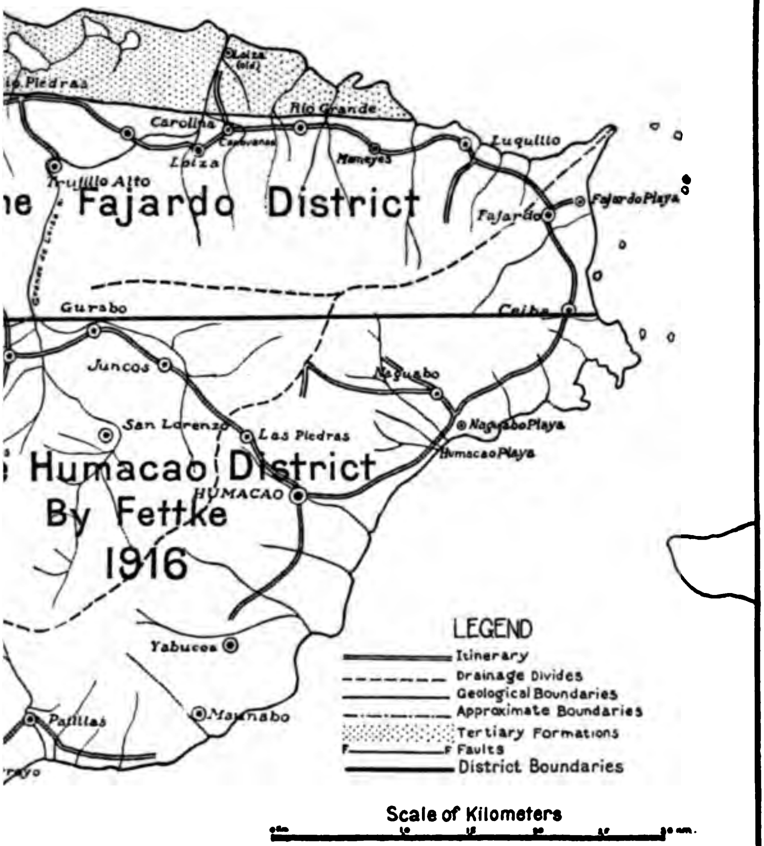
Mineral Resources.—Considerable money has been spent in Porto Rico in mineral exploration. It is said that gold was secured in paying quantities by the Spaniards in the early days. One can see gold panning in a few places now. Many ores of other metals are also formed as well as other economic products. Almost none, however, have proven attractive as the basis of an industry, although much interest is attached to such possibilities. Mineral resources of sufficient value to establish these industries are much to be desired, and it is one of the purposes of this Survey to make a final summary of all matters relating to this question in a general study after all of the districts have been fully investigated and reported.

DISTRICT STUDIES, WITH OUTLINE MAP

The basis of all detailed investigations is the district or areal study. It has been found possible to divide the island into areas, each of such size that it could be studied in sufficient detail for the purpose in a single season by one man. These districts are not necessarily of the same size or form. Their boundaries have been chosen, in part, in consideration of transportation facilities and field accommodation, and, in part, in consideration of the occurrence of special features deserving particular attention or special study. It has been possible to assign to each investigator of a district of this kind some important problem of a fundamental sort in addition to his regular district mapping and description. On this basis the area of the whole island has been covered by seven districts. They vary considerably in size, depending upon the nature of the country and somewhat upon the complexity of the geological problem, and to some degree also on the amount of previous investigation in adjoining areas (see outline map).

The first two districts to be studied completed a broad belt entirely across the island from north to south, extending from San Juan to a point beyond Vega Baja along the north coast and from Guayama to a short distance beyond Santa Isabel along the south coast. This belt was chosen as a guide study and was intended to more firmly establish the major geological lines for further study of the rest of the island.

The belt across the island was divided by a line from east to west in the vicinity of Barranquitas into a northerly and a southerly district.


Piedras
Loiza (old)
Rio Grande
Carolina
Canovanas
Loiza
Mameyes
Luquillo
Trujillo Alto
he Fajardo District
Fajardo
Fajardo Playa
Grande de Loiza
Gurabo
Ceiba
Juncos
Naguabo
San Lorenzo
Las Piedras
Naguabo Playa
Humacao Playa
Humacao District
HUMACAO
By Fettke
1916
Yabucoa
Patillas
Maunabo
rroyo
LEGEND
Itinerary
Drainage Divides
Geological Boundaries
Approximate Boundaries
Tertiary Formations
F F Faults
District Boundaries
Scale of Kilometers
10
15
20
25
30 km.

The northerly one has for convenience been designated the **San Juan District** from its principal city. A study of this district was completed by Mr. Douglas R. Semmes and the report on its geology, with geologic map, forms a part of this bulletin.

The south end of the belt, south of Barranquitas, was studied by Mr. E. T. Hodge. His area has been commonly referred to as the **Coamo-Guayama District**. A special study of the nature and probable origin of the hot springs at Coamo has been included by Mr. Hodge in his studies of this district.

The **Aguadilla-Lares District** occupies the northwest corner of the island, extending southwest as far as Mayaguez. This was studied in 1916 by Mr. Bela Hubbard. The district includes the best material for a detailed investigation of the Tertiary stratigraphy.

The **Humacao District** of the southeast corner of the island extends as far west as Guayama and as far north as Ceiba. This district contains one of the large areas of granite as well as the principal iron occurrence. The geology of this district was studied by Dr. Fettke in 1916. It involves these special discussions in addition to the district geology.

The **Ponce District** of the south and southwest quarter of the island extends from a few miles east of Juana Diaz to the west coast and from the south margin to Mayaguez. This was studied by Mr. Mitchell in 1917 and was made to include the special problem of elevation and subsidence as marked by terraces, and also the problem of faulting.

Two other districts are still to be studied.

One lies in the northeast corner, occupying the area north of the Humacao District, and may be called the **Fajardo District**. The other lies west of the San Juan District, extending to the vicinity of Camuy on the west and Adjuntas and the mountain divide to the south, where it touches the Ponce District. This is known as the **Arecibo District**.

The accompanying outline map indicates the location of these districts and gives the names of the men who have been responsible for their individual study (see outline map).

SPECIAL INVESTIGATIONS

Special scientific studies not already covered by the general investigations of group (*a*) or included in the district studies of group (*b*) are chiefly concerned with pure science investigations connected with paleontology. Immense collections have been made and seem to be worthy of elaborate study. It is expected that they may ultimately form a volume on the paleontology of Porto Rico.

A considerable list of special topics enumerated in the original Reconnaissance do not deserve so elaborate treatment as that suggested above, and indeed are quite logically cared for in the different district studies. Some of them have been mentioned in that connection already. Among those considered as representatives of the class are the following:

(*a*) Mapable subdivision of the Younger Series.
(*b*) Mapable subdivision of the Older Series Complex.
(*c*) Nature and origin of the San Juan formation.
(*d*) Reef-building organisms.
(*e*) Changes in character and composition of the igneous products at different stages in Porto Rico volcanic history.
(*f*) Thermal springs.
(*g*) Studies in magmatic differentiation in an isolated volcanic center.
(*h*) Origin of the Iron Ores, etc., etc.

An occasional special topic has been the basis of a separate paper (Fettke and Hubbard, 1918), and some of these have been or will be published separately in an effort to furnish useful information as promptly as possible.

In spite of the complexity and extent of the original undertaking, most of it has already been completed so far as relates to the general studies, district descriptions and special problems. One season's field-work on the scale of that of 1915 or 1916 would complete such work, and it would then be possible to make a final geological map of the island and to write the summary of its areal, structural and economic geology and its geological history.

A completion of it to that consummation may be regarded as the immediate object of these geological field studies. The paleontologic studies, in so far as they are necessary to the historical treatment and stratigraphy, are to be included in the geologic investigations. Subsequent studies of all kinds and to any extent may be based on the collections, and additional investigations along paleontologic lines will then be included in a separate volume under paleontology.

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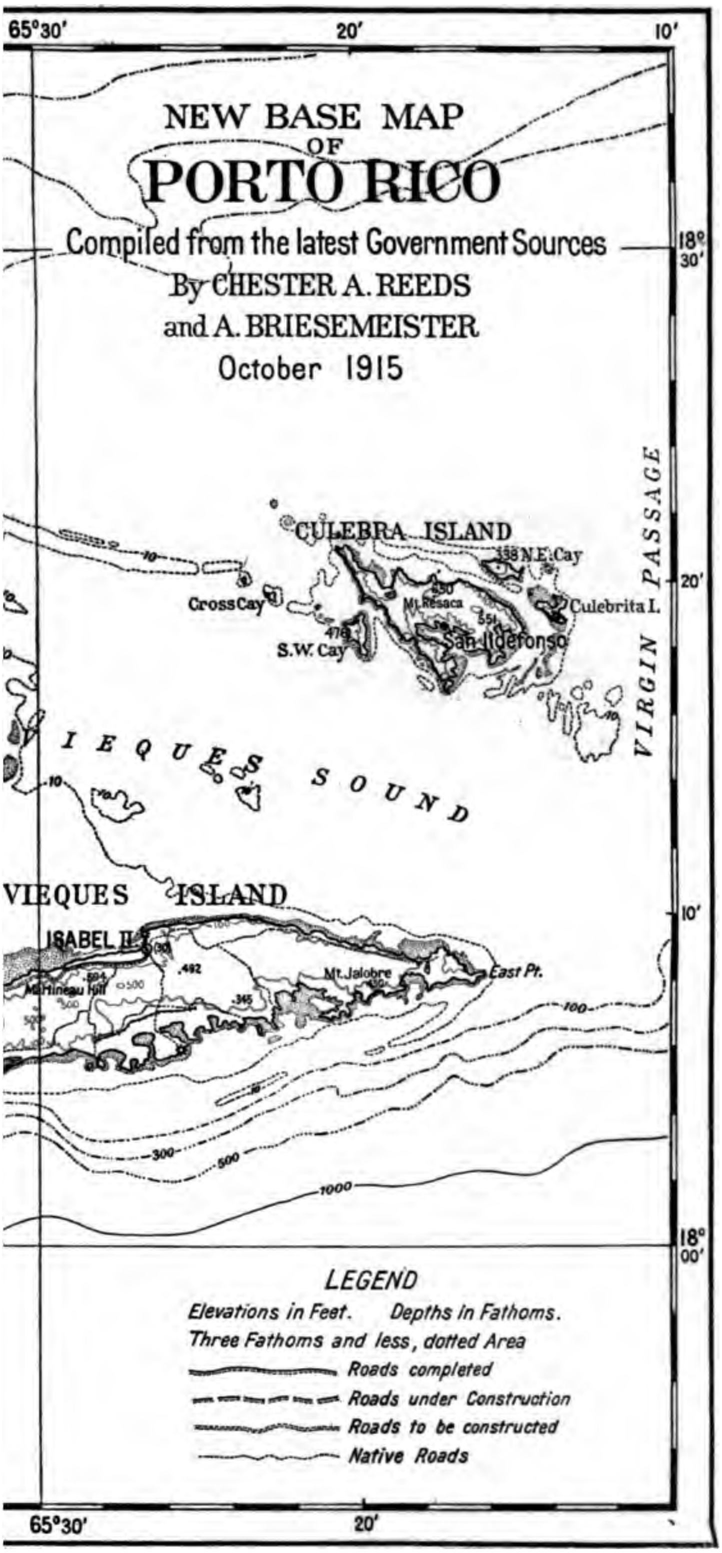
NEW BASE MAP OF PORTO RICO

By Chester A. Reeds

Following a short fossil-collecting season in Porto Rico in June and July, 1915, for the New York Academy of Sciences and the Porto Rican Government, the American Museum of Natural History cooperating, it seemed desirable for plotting results that a small outline map of Porto Rico should be prepared. During October, 1915, such a map was drawn at The American Museum of Natural History by Mr. A. Briesemeister under my direction. Most of the data for the base sheet was obtained from a large map which had been prepared by the engineers of the Interior Department of the Porto Rican Government. The four-sheet edition of the U. S. Coast and Geodetic Survey and the U. S. Post Route map of Porto Rico were also used. Before the end of October a solio print edition of one hundred copies of this new base map of Porto Rico was published by The American Museum of Natural History. Complimentary copies of the preliminary edition were distributed to the members of the Porto Rican Committee of the New York Academy of Sciences, to certain officials of the Porto Rican Government, to the various field men sent out by the New York Academy of Sciences to Porto Rico and to other interested persons.

During December, 1915, the 100, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000 and 4500 foot contour lines were drawn on a separate sheet for superposition on the base map of Porto Rico which had been prepared in October. Data for this topographic map of the island were taken from various sources, chiefly the U. S. Coast and Geodetic Survey maps, the profiles and sketches of the engineers of the Porto Rican Highways Commission, the contour map of a portion of the south side of the island prepared by the Irrigation Service, the U. S. Geological Survey's topographic sheet of the Luquillo Forest Reservation, together with H. M. Wilson's topographic map of Porto Rico, prepared for the U. S. Water Supply and Irrigation Paper No. 32, 1899. Numerous photographs by Professors C. P. Berkey and H. E. Crampton of the Porto Rican Committee of the New York Academy of Sciences as well as a large number by myself were of considerable assistance in the preparation of the topographic sheet. Fifty solio print copies of this contour map were issued


NEW BASE MAP
OF
PORTO RICO
Compiled from the latest Government Sources
By CHESTER A. REEDS
and A. BRIESEMEISTER
October 1915
65°30'
20'
10'
18° 30'
20'
10'
18° 00'
CULEBRA ISLAND
338 N.E. Cay
Cross Cay
Mt. Resaca
551
Culebrita I.
476
S.W. Cay
San Ildefonso
VIRGIN PASSAGE
VIEQUES SOUND
VIEQUES ISLAND
ISABEL II
Mt. Hineau Hill
492
Mt. Jalobre
East Pt.
10
100
300
500
1000
LEGEND
Elevations in Feet. Depths in Fathoms.
Three Fathoms and less, dotted Area
Roads completed
Roads under Construction
Roads to be constructed
Native Roads

by the Museum and complimentary copies were distributed as had been done with the base map.

Early in 1916 the 10, 100, 300, 500 and 1000 fathom lines were added to the base sheet of October, 1915. Areas less than three fathoms in depth were dotted. This information was compiled from the various Porto Rican charts of the U. S. Coast and Geodetic Survey.

This map should be of interest not only to the scientist and tourist but also to the million inhabitants of Porto Rico, for it is legible, convenient in size and contains a vast amount of information.

THE GEOLOGY OF THE SAN JUAN DISTRICT, PORTO RICO

By Douglas R. Semmes

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SYNOPSIS

The area described in this report, which has been designated the San Juan district, lies on the northern side of the island of Porto Rico. It extends from the city of San Juan on the east to a point about two miles east of Manati and southward as far as Barranquitas—an area roughly 500 square miles in extent. The San Juan district is a typical north-south section through the northern half of the island, the geologic and physiographic history of which may be regarded as essentially the same as that of the whole island.

The physiographic history of the San Juan district is that of a complex mountainous oldland, which has been peneplaned, partially submerged, overlapped by a coastal plain, uplifted, maturely dissected, again slightly submerged and partially uplifted, erosion continuing in the interior from the time of first uplift.

The formations of the district may be primarily divided into the younger series, or those that form the coastal plain, and the older series, or those that lie below it. The youngest formation consists of a coastal deposit of indurated lime dune sand of presumably Pleistocene age overlying unconformably a limestone series, which forms the coastal plain proper. This limestone series, termed by Berkey the Arecibo formation, lies almost horizontal (dip 6° N.) and is now maturely dissected, giving rise to the typical *pepino* or haystack topography of the island. The Arecibo formation is regarded as upper Oligocene in age. In the northwestern portion of the island, but not appearing in the San Juan district, is a lignitic shale member (the San Sebastian shale) which underlies the Arecibo formation. The age of this shale member is uncertain, but in all probability it is lower Oligocene.

The older series consists of marine and volcanic sediments with numerous intrusives. It is highly tilted and locally folded, resting unconformably below the younger series. The sedimentary types represented are limestone, shales, sandstones, conglomerates, tuffs and ashes. With hardly an exception, these sediments are either of volcanic origin or were deposited through volcanic processes. Even the limestones show brecciated structure and are, with few exceptions, merely accumulations of limestone fragments derived from older beds shattered by volcanic outbursts. The foraminiferal content of certain shale and limestone beds in the upper part of the older series indicates that the beds are upper Cretaceous and Eocene in age. The lower part of the series is no doubt Comanchic. The peneplanation of the older series culminated along the coast before the deposition of the coastal plain, for the peneplane surface can now be traced underlying the Arecibo formation. In the interior, however, erosion continued until the uplift, which occurred in late Oligocene time.

The older series is everywhere intruded by igneous rocks of many varieties. The predominant type is an andesitic porphyry. The tuffs and other sediments directly derived from volcanic sources are also of this general composition. The igneous rocks occur as extrusive sheets, sills, dikes, and small and moderate sized stock-like intrusives.

The mineral resources of the district are not large. About 100 ounces of gold are panned annually from the rivers in the vicinity of Corozal. Gold quartz veins have been worked in the hills south of Corozal, but without success. In the barrio Pasto, southwest of Morovis, several copper prospects have been slightly explored.

INTRODUCTION

The Antilles and the Central American region have remained until the close of the nineteenth century almost a *terra incognita* as regards their geological structure and history. Unfortunately, little study has since been devoted to this critical region which connects the two Americas, and until more accurate information regarding it is available our ideas of the geologic correlation of the two continents must remain largely conjectural. At the close of the Spanish-American war Porto Rico, being the closest of our newly acquired insular possessions, attracted a good deal of attention. During the first years of the American occupation much was written about the island and its inhabitants. Several very good papers describing its general configuration and geology were published during this period,[1] and a number of articles on particular features or the general aspects of the country appeared in current periodicals and in proceedings of learned societies. Interest in Porto Rico, however, soon waned, and from 1902 to 1915 nothing regarding its geology was published. In 1915 a paper by C. P. Berkey appeared in the Annals of this Academy, which gives the first detailed and purely geological description of the island that has yet been written.

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[1] Dorsey (1902), Hill (1899*a*), (1899*c*), Wilson (1899), (1900).

Geographic Location

Porto Rico, the smallest and easternmost of the Greater Antilles, averages 35 miles in width and 100 miles in length, presenting a regular rectangular outline three times as long as broad and alined nearly exactly east-west. Its shoreline is nearly straight and quite regular. The coast is usually low, with a few low promontories. The fringing keys and deep indentations characteristic of a more youthful stage in coastal development, and so abundantly developed on the Cuban coast, are entirely wanting. Its area is 3670 square miles, just 500 square miles less than the area of Jamaica, or about three times that of Rhode Island. Its population, considered as a whole, is the densest of any country on the globe.

Natural History Survey of Porto Rico

In 1914 an appropriation was made by the Insular Government of Porto Rico for the establishment of a Natural History Survey which was to be carried on in conjunction with the New York Academy of Sciences. The geological phase of the survey was begun in 1914 when Dr. Berkey and Dr. Fenner spent a month on the island, making a geological reconnaissance, preparatory to a subsequent and more detailed survey. The following year the writer was assigned to the San Juan district to begin this more detailed work.

San Juan District

The region selected may best be called the San Juan district, as San Juan, the capital, is situated in the northeastern corner. The district is that area comprised between longitude 66° 05′ and 66° 27′ west, and an east-west line through the town of Barranquitas about 21 miles south of the northern coast. The areal extent of the district is roughly 500 square miles. A corresponding area of similar width to the south was studied at the same time by Mr. E. T. Hodge. In this way a belt 25 miles wide was surveyed entirely across a typical portion of the island. Three months were spent in the field, in which time a topographic map was constructed, the mineral resources studied, and the geology plotted in as much detail as possible, considering the shortness of the time and the size of the area involved.

THE PHYSIOGRAPHY OF THE ISLAND

The general configuration and topography of the island have been well described by several writers. Dorsey (1902) has written an admirable description of the several types of topography one meets on crossing the island, with an especially detailed description of the limestone topography of the coastal plain. Wilson (1899) also has given a good general description of the physical aspects, and Hill (1899) described the physiography in connection with his geological reconnoissance of the island. The recent article by Berkey (1915) gives the most modern and detailed description of the physiography and physiographic history of the island.

The island of Porto Rico may be described as a complex mountainous oldland, in the n^{th} cycle of development, which has been peneplaned, or reduced to an old stage of topographic development, submerged, overlapped by a coastal plain, uplifted and maturely dissected, partially submerged, then re-uplifted and further dissected.

COMPLEX MOUNTAINOUS OLDLAND

The most characteristic topographic feature of Porto Rico is its complex mountainous aspect. That portion of the island that rises above sea level is merely the eroded crest of a submerged mountain range of great complexity and magnitude. This eroded crest rises steeply from the sea to an average altitude of 2500 feet along the divide. Owing to difference in rainfall on the northern and southern side, the divide has been pushed to the south by the encroachment of the larger northern streams until it now stands two-thirds of the way toward the southern coast. The present position of the divide has also been accounted for by a theory of block faulting of the whole island with the front face of the block facing south (Berkey, 1915, p. 40). In the western portion of the island the divide is double, where it is parted by westerly flowing streams. Near Adjuntas the two divides join at the headwaters of the Anasco River to form a single ridge, which continues to Cayey, where it first swings southward, and then sharply to the northeastern corner of the island. The Luquillo range forms another westward extending branch of the divide nearer the northern coast.

The texture of the mountainous topography is medium to fine, except for certain lowland areas of coarser texture. The interior topography is predominantly the ridge or *cuchilla* type. The slopes are extraordinarily steep, slopes of 30–40 degrees being often seen. Between these ridges the streams run in V-shaped valleys. Some of the valley walls are very steep, but all variations from a canyon-like gorge to mature, open valleys are to be found. The streams north of the divide are very numerous and of large volume, due to the abundant precipitation of the large per cent of run-off. Loisa, the largest river, rises only eight miles north of Arroyo on the southern coast. The Plata, next in size, rises the same distance north of Guayama. The larger streams rise high up in the mountains, and in the first few miles develop steep gradients characterized by falls, rapids and boulder-strewn beds (Fig. 1); then passing out into the lower coastal margins they acquire much more mature courses and finally swing in large meanders over the flat playa plains bordering the coast. Thus a typical stream such as the Plata on the northern coast may show every stage in development from youth to late maturity in its comparatively short course to the sea. The complexity of this mountainous old-

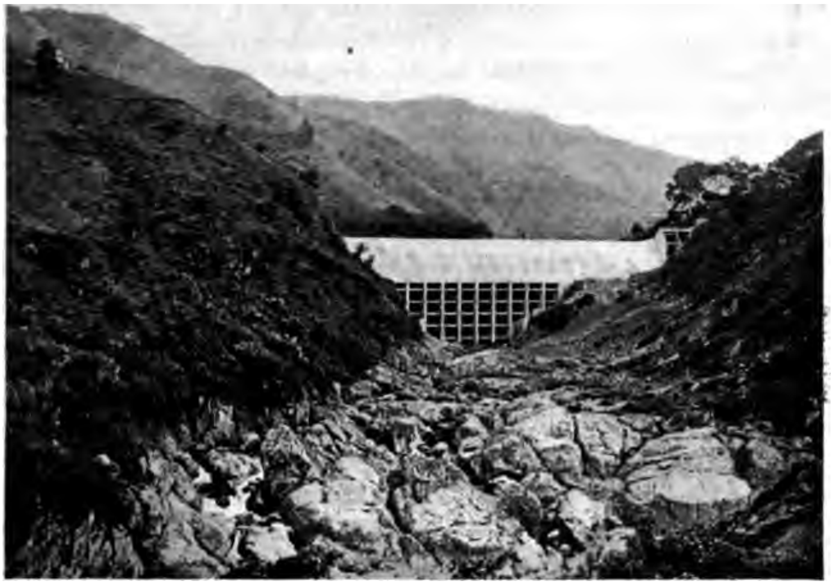


FIG. 1.—*Valley of the Plata, just below the power dam at K 19, Comerio Road*

Such steep valley walls and boulder-strewn beds are characteristic of almost all of the mountain streams.

land is readily recognized from even the most cursory observation of its geologic structure. An endless variety of sediments and volcanics, steeply tilted and locally folded, are to be found intruded, permeated, and saturated by igneous rocks of many kinds, assuming an endless variety of forms.

PENEPLANATION

If one stands upon the summit of one of the central sierras and looks out over the innumerable ridges that rise in all directions he may be impressed by the even crest line formed by the general accordance of summits. This crest line apparently marks the present level of a peneplane the development of which began in Eocene and culminated in late Oligocene time. It is quite possible that the peneplane was never developed in any degree of perfection over the entire island. In some districts, however, its present position is clearly defined, and near Mayaguez and Rincon undissected portions of this old upland surface can be seen. In this vicinity the level-topped areas are locally known as mesas. In other parts of the island no trace of an accordant skyline can be found. However, a discordant skyline might well be developed in local areas through differential erosion or by subsequent warping. The evidences for and against peneplanation are discussed in more detail in another part of this report.

The present elevation of the peneplane ranges from 2000 to 2200 feet near the divide to sea level along the coast. On the northern side it is partially covered by the younger coastal plain strata, but in the stream valleys it can be seen still preserved beneath the coastal plain. Elevations rising decidedly above its maximum elevation, such as El Yunke (3790 feet), Los Picachos (3700 feet), Ala de la Piedra (3650 feet) and Guilarte (3600 feet), must be regarded as monadnocks upon the peneplane surface.

THE COASTAL PLAIN

Overlapping the mountainous region, there extends for nearly the whole length of the northern coast a coastal plain of limestone and shaly beds, which reaches as far inland as Lares and to an elevation of 1200 feet. A similar coastal plain appears along the central portion of the southern coast. They are both of early Tertiary age, but whether they are exactly contemporaneous is uncertain. This fringing coastal plain varies in width from a mere line of isolated limestone hills, as seen south of San Juan, to a belt over ten miles broad north of Lares. On the southern coast it nowhere exceeds two or three miles in width. Overlying the coastal plain on the northern side, and occurring as a string of fringing islands or low coastal promontories, is the San Juan lime sand. It is essentially an indurated dune sand composed of shell fragments and quartz grains. This sand extends nearly the whole length of the northern coast, except for the extreme eastern part, but it has not yet been reported upon the southern coast.

Mature Dissection

The coastal plain is characteristically mature in its stage of development. Some portions of it might be regarded as sub-mature, and towards the eastern end of the district, south of San Juan, dissection has continued to late maturity. The larger area comprised between these two extremes, however, shows the rugged appearance of maximum dissection, characteristic of maturity.

Recent Submergence and Uplift

Since the deposition and uplift of the Tertiary coastal plain there is evidence of still later movement. The rock terraces described by Berkey (1915, p. 48) on the southern side of the island indicate that the sea was once at that level, while the presence upon them of recent shells fixes the time. On the northern coast recent marine shells are found some distance up the larger valleys at elevations of 100–200 feet. The subsequent uplift was not as great as the previous subsidence, for large areas of the San Juan sandstone, which must have originated at or above sea level, are now submerged, forming islands fringing the coast. The available evidence seems to indicate, moreover, a series of minor oscillations extending from Pleistocene time until the present, that is, the submergence which formed the fringing island was not continuous but consisted of numerous positive as well as negative movements.

THE PHYSIOGRAPHY OF THE SAN JUAN DISTRICT

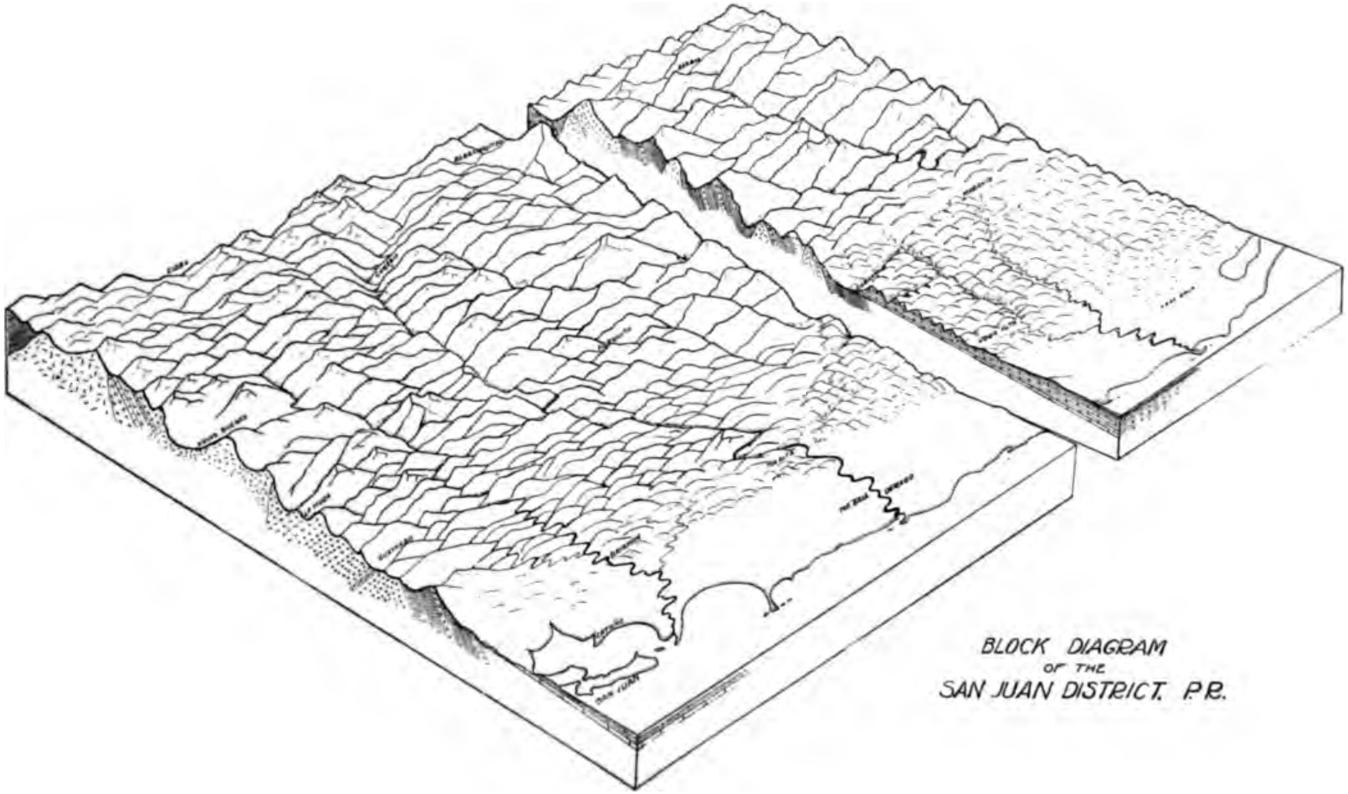
The San Juan district, as already stated, extends from San Juan westward to a point two miles east of Manati and southward as far as Barranquitas. Lying in the central part of the northern side of the island, it enjoys a very uniform humid climate. The mean annual rainfall varies from 50 to 90 inches. The dryest months are December and January, and the wettest month is May. The mean annual temperature varies from 74° to 78°. Though the climate is strictly tropical, the heat is rarely oppressive; a breeze is always stirring, and at least one or two showers may be expected each day.

The district represents a typical section of the northern half of the island, and its physiographic history has in general been the same as that given for the island as a whole. The accompanying block diagram (Pl. I) is an attempt to picture graphically the topography of the San Juan district. Traversing the district from the coast to the southern boundary, one would cross successive belts of differing topography, which may be regarded as the topographic provinces of the district. On the coast is a narrow belt of modern sand dunes, in some places overlying the older Pleistocene consolidated sand dunes. Following this, there is an expanse of flat plains locally known as playas. These extend from the coastal dune area inland to the Tertiary limestones. In places the flat expanse of the playas is broken by low, rounded hills of the Tertiary limestones rising through it. To the south of the playa plains the typical *pepino* or haystack topography of the limestone belt begins. This belt extends inland and adjoins the oldland. It is occasionally broken by transverse valleys, such as the valleys of the Plata and Cibuco Rivers, which have completely removed all the limestone so that the alluvial plains of the river valleys rest directly on the oldland. Separating the coastal plain and the mountains proper is a low-lying area called by Hill (1899*a*) the "parting valley." This is the inner lowland developed between the coastal plain cuesta and the oldland. It is well developed as it crosses the San Juan district, broadening out towards the east to form a lowland area several miles wide between Bayamon and Guaynabo. The mountainous area extends southward from the inner lowland to the southern boundary of the district.

THE DUNE AREA

The dune area presents topography of two types: first, the low promontories and coastal islands developed in the consolidated dune sand of Pleistocene (?) age; and, second, the modern dune topography that borders the coast. The first type is best represented in San Juan City. The promontory, rising some 75 feet above the sea, on which the city stands, is entirely made up of the consolidated dune sand. To the west it can be traced either as a string of low islands, or occasionally as a promontory jutting out into the sea. Near Vega Baja Playa the island type is well developed, the islands ranging in size from a few yards to several hundred yards in length, and occurring out as far as a quarter of a mile from the coast (Fig. 2).

The second or modern dune type of topography is a narrow strip of live dunes composed of lime sand similar in composition to that which forms the consolidated deposits. The dune belt follows the coast for the entire length of the district, varying in width from a few feet to several



BLOCK DIAGRAM
OF THE
SAN JUAN DISTRICT. P.R.

hundred yards. It is broadest in the western part of the district, but its maximum width is developed farther west than the San Juan district extends. The origin and source of the Pleistocene, as well as the modern dune sand, will be discussed under a subsequent heading.

THE PLAYAS

The playa plains, a name given by Hill to the fan-like plains that extend from the foothills of the dissected limestone cuesta to the coast, are to be seen along the entire coast of the San Juan district. Separated from the sea by the dune belt, they extend inland to the Tertiary limestones, and follow up the larger valley until they lie directly on the rocks at the interior complex. The playa plains rise only a few feet above sea level, and until recent years large areas of the plains in the San Juan district have been covered with water, forming inland swamps and lagoons. Since the value of the land has been recognized for sugar-cane production, all the available areas have been drained, and now constitute the most productive and valuable lands on the island. The low, flat, monotonous expanse of the playa plains is occasionally broken by low, rounded hills of the Tertiary limestones rising above the alluvial (Fig. 3). These limestone hills are isolated remnants of the coastal plain here buried beneath the recent deposits. Owing to the slight elevation that they afford above the blistering heat of the surrounding plains, they are selected as town and dwelling sites. Both Dorado and Toa Baja, the only two towns

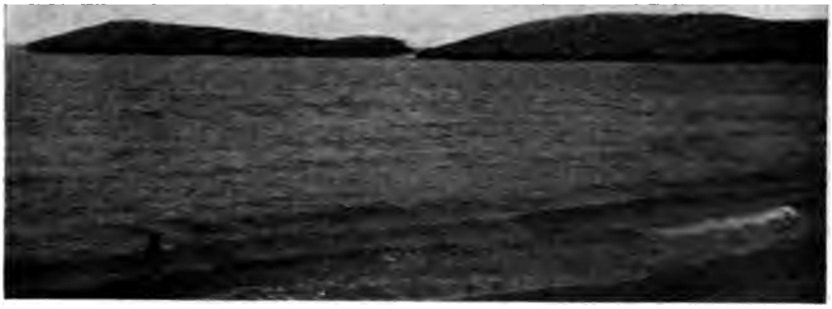


FIG. 2.—*San Juan consolidated dune sand forming fringing islands at Vega Baja Playa*

situated in the center of the playas, are built upon these limestone remnants. Others are chosen as sites for the individual dwellings of the natives. The playa plains follow the three principal valleys of the Cibuco, Plata, and Bayamon Rivers for some distance inland, and in the case of the latter two extend well beyond the limestone belt.

The geological history of the formation of the playa plains has, no doubt, been complex. It is evident that they are in part of fluvial origin, for they grade directly into the true alluvial plains of the river valley. Just how important a rôle the sea has played in their formation is not definitely known. It is the writer's opinion, however, that both factors have been influential. This point will be further discussed below.

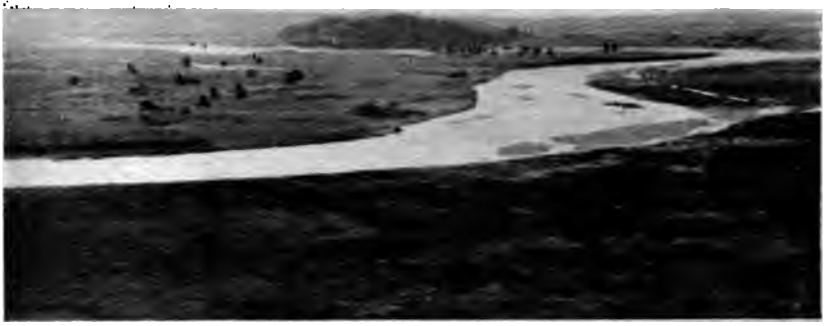


FIG. 3.—*The playa plains near Arecibo*

Showing a limestone remnant rising above the floodplain deposits and the limestone hills of the Arecibo formation in the background. Photographed from report of Bureau of Soils, U. S. Department of Agriculture, 1902.

THE TERTIARY LIMESTONE BELT

As the northern coast of Porto Rico is approached, one readily distinguishes two kinds of topography; the rugged mountainous skyline, and the lower, angular, maturely dissected limestone coastal plain. On closer inspection it is seen that the topography of the coastal plain consists of numerous isolated or closely grouped angular hills not exceeding 100 feet in altitude, but of such angular and rugged outline, and so densely covered with tropical vegetation that they form the most inaccessible and impassable regions of the district. Slopes of 40° are quite common and occasionally vertical faces of limestone rising 10 or 20 feet are to be seen. Though from a distance the hills appear well rounded, yet at close range they are exceedingly rough and jagged, and are, as one of the Americans living in the vicinity expressed it, "very hard to scramble up." The unusual appearance of these limestone hills was early noticed by the natives, who call them *pepinos* or cucumber-shaped hills. Berkey has used the term "haystack hills," a term peculiarly fitted to picture their appearance, rising abruptly as they do from comparatively level plains (Fig. 4).

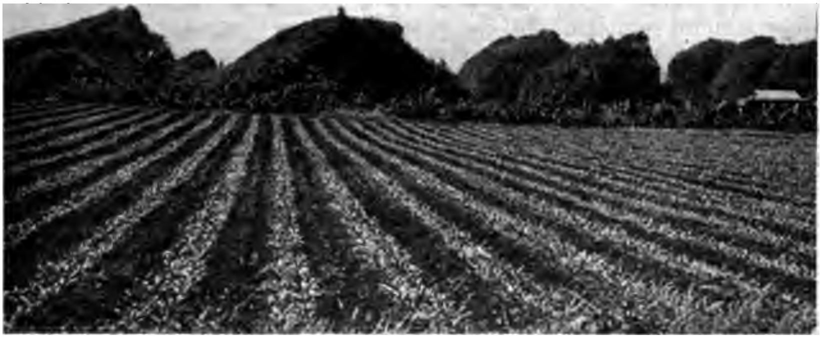


FIG. 4.—*Typical haystack topography as developed in the western portion of the San Juan District*

Photographed by H. E. Crampton.

Both Dorsey (1902, p. 800) and Berkey (1915, p. 52) have independently come to the same conclusion as to the origin of the haystack topography. Berkey summarized the steps in their development as follows:

> The reef limestones are not uniform in composition or structure. They have more or less intermixture of earthy matters which are distributed irregu-

larly but chiefly at certain horizons, as more earthy or shaly beds of no very great lateral or vertical extent. Such conditions are repeated at occasional intervals in successive horizons. As such a series is lifted above sea level and subjected to ordinary erosion and weathering, the tendency is, (a) for the purer and more massive reef limestones to be attacked by the solvent action of percolating water with a development of underground channels, porous rock condition and actual caverns, (b) for the more earthy layers to resist and limit such action at the levels where this matter is present in sufficient abundance, with a development of residuary material. As this action progresses toward maturity, many of the larger caves collapse and sink-holes are thus formed. With still further development, the sink-holes merge into each other in local areas where solution has been most active, the earthy debris forms a soil in the bottom corresponding in level with the first important earthy layer, and adjacent remnants of the limestone reef stand out as sharp, rugged hills separated by irregular notches that represent other smaller, collapsed caves. The result of such action and conditions, finally, is the numerous 'haystack' hills standing on flat soil-covered areas or surrounding such areas as if they were just set down as bunches on the surface.

This is no doubt the best explanation for the origin of the typical haystack hills. Towards the south boundary of the limestone belt, however, the haystack hills are not typically developed. The topography of this region is more rounded, with better drainage pattern. Occasional sink-holes are developed, but the topography as a whole resembles more that developed by normal stream erosion. This difference is due to the change in character of the limestone. The haystack type is developed on pure limestone, the latter on shaly limestone and shales.

TERRACES

The haystack hills rise abruptly from almost level plains, just as haystacks on a grass field. The plains are local developments and do not continue over extended areas. On passing from one of these plains to another, one is conscious of the fact that they rarely are of the same altitude, that is, they are not separated portions of a continuous base-level. On the contrary, they assume a step-like succession, forming a series of seaward-facing terraces. The level of an upper terrace corresponds roughly with the summits of the haystack hills on the next succeeding lower terrace. The terraces are best developed west of Vega Baja. Two can be recognized on following the road from Vega Baja to Morovis at K[2] 42-43 and K 3-4 (Morovis road) respectively (see topographic map). Others less prominent can be detected by means of the aneroid.

There are two possible explanations for the origin of the terraces:

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[2] K indicates kilometer posts on the public roads.

(*a*) The presence of a shaly layer in the purer reef limestones may be the controlling factor in the development of a plain at a particular level through difference in solubility. The pure limestone would soon develop large caves, extending down to the level of the shaly layer, which, collapsing, would leave the haystack hills on a fairly level base. This plain would slope gently with the limestone strata towards the sea. After a time erosion would finally break through the shaly layer and a new terrace would be formed with the next shaly layer as its base (Fig. 5). In this way successive terraces would be formed facing the sea. The difference in appearance of the pure limestone and the shaly layers might well be so slight as to escape notice, so the apparent absence of shaly beds throughout the upper limestones would not disprove the theory. The writer located several shaly beds in the upper limestone that might easily have caused the terraces, but no exact correlation could be made from the barometric readings.

(*b*) It is also possible that these may be marine terraces. Evidence for recent subsidence has already been mentioned, and marine terraces of about the same elevation have been described from the southern coast (Berkey, 1915, p. 48). Both causes may have been influential, but the writer is inclined to adopt the first, since no marine shells have yet been found on the terraces. Moreover, the haystacks on the plains are more numerous and more promiscuously scattered than marine stacks should be, unless one considers the possibility of marine terraces later dissected to form the haystack hills.

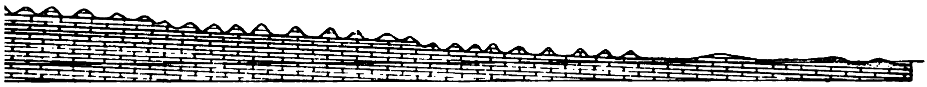


FIG. 5.—*Section through the Arecibo formation*

Illustrating the possible origin of terraces from differential solution caused by shaly layers at A, B and C.

The limestone belt extends across the whole district. It is wedge-like in general outline, being about five miles wide on the western border of the district, and thinning to a mere string of isolated hills on the east. Its inner margin reaches the elevation of 700–800 feet north of Corozal. In this locality and to the west its southern boundary is a well-defined cuesta which is locally known as "The Walls" (Fig. 6). To the east of Corozal the cuesta form is destroyed by more advanced erosion.

THE INNER LOWLAND

This topographic province, described by Hill as the "parting valley" (Hill, 1899*a*, p. 105), extends entirely across the San Juan District. It lies between the infacing cuesta of the coastal plain on the northern and the mountainous region to the south. It is best defined at Corozal (Fig. 7) and to the west. Eastward it broadens as the limestone cuesta wedges out, until south of Bayamon it is represented by a broad expanse of rolling country, extending southward past Guaynabo and merging gradually into the interior mountain. Its topographic development is more than that of the interior mountains, that is, its stage of development is late maturity, with mature streams crossing it in broad and often meandering courses.

THE INTERIOR MOUNTAINOUS REGION

South of the inner lowlands the topography of the San Juan District is typically mountainous. On approaching the island the rugged serrate character of the skyline can be distinguished soon after its outline rises above the horizon. Passing through the mountainous area one is impressed with the extreme degree of the dissection. Almost no level ground is to be seen. Throughout most of the mountainous region of the San Juan District the country has attained the maximum ruggedness characteristic of a fully mature stage in topographic development. Other portions show more or less advanced stages, but the topography of the region as a whole is mature. Between the numerous streams the divides form a network of sharp ridges, so steep that the natives have appropriately named them *cuchillas* or knives. These are likewise closely and deeply corrugated by ravines and gullies, the whole region assuming very much the appearance of a wrinkled handkerchief, a simile said to have

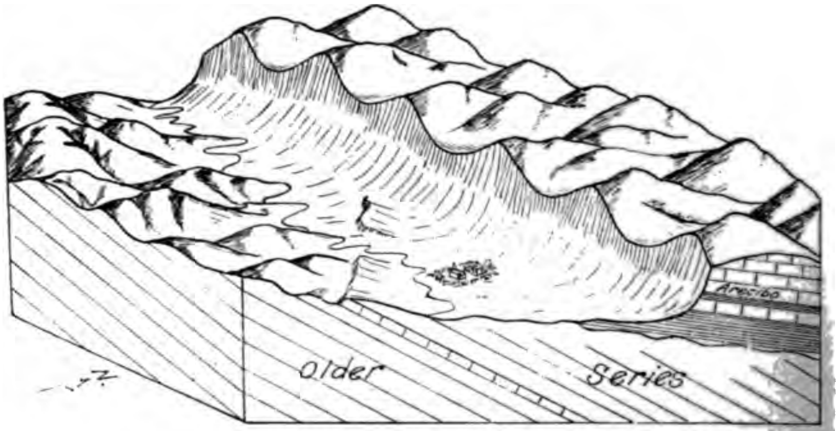


FIG. 6.—*Inface of cuesta and inner lowland near Corozal*

Showing relation of the Corozal limestone in the older series.

been used by Columbus in describing the topography of the Antilles to Queen Isabella.

The drainage of the mountainous area as a whole is dendritic in pattern. The adjustment of the stream courses to underground structure is very rare. A few cases were noted where some adjustment had taken place, but nowhere was it conspicuous. Although the mountainous region is underlain by a complex of formations of much variety, yet there is little or no evidence of this in the topography. Occasionally a dike could be traced for a short distance as a poorly discernible ridge, and it was noticed that the highest points were usually underlain by highly indurated siliceous tuffs, as, for example, Torrecillo, northwest of Barranquitas, and Helechal, some distance south of Bayamon.

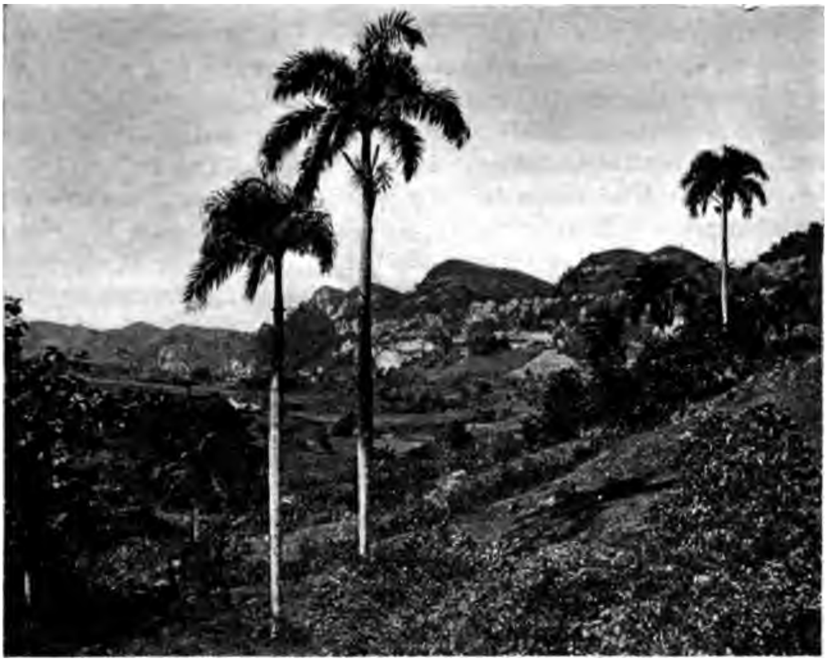


FIG. 7.—*The inner lowland and the inface of the cuesta at Corozal*

The almost vertical inface is locally known as "The Walls." Photographed by H. E. Crampton.

INCISED MEANDERS

Some of the streams have developed deeply intrenched meanders as they pass out from the mountainous oldland. The best example is that of the Orocovis River south of Morovis. In this region the stream shows larger swinging meanders entrenched to the depth of 800–1000 feet (see topographic map). The origin of these incised meanders and their restriction to the inner lowland and the adjoining mountainous region is comparatively simple. At the time peneplanation reached its maximum the streams passing out over the flat oldland surface acquired meandering courses on nearing the sea, which then reached inland as far as the present mountainous region. Subsequent gradual uplift has slowly entrenched these meanders as the coastal plain emerged and assumed the present position.

STREAM CAPTURE

Although there are undoubted cases of stream capture in other portions of the island, no striking examples are to be found in the San Juan district. Near Comerio, however, there is a wind gap that was evidently at one time occupied by a tributary of the Plata River. This tributary, now represented by Mora Creek, formerly flowed from the southeast through the wind gap and occupied the upper valley of the Arroyato River (see topographic map). Subsequently another tributary of the Plata, working down from the north, intercepted the larger stream, forming the present Arroyato River, which joins the Plata at K 23 on the Comerio Road. Both streams are now completely readjusted, but it is still evident that Mora Creek occupies a much larger valley than would be expected, considering its volume.

PENEPLANE

It has already been stated that the interior mountainous region has been partially truncated by peneplanation. In the San Juan district practically nothing of the upland surface remains. In some portions, however, its present elevation is well marked by the even character of the crest line. In the southern part of the district it can be traced at an elevation of 2000–2200 feet or less towards the eastern corner. From this elevation it slopes to the edge of the mountainous region, where it is approximately 1200 feet. At this point the mountainous region breaks sharply down to the inner lowland, forming a well-defined escarpment. The escarpment can readily be traced on the topographic map, especially in the central portion of the district just north of Naranjito. The peneplane level, occasionally discernible among the crests south of the escarpment, is not again recognizable until it plunges below the limestone strata of the coastal plain. At Corozal its elevation as it passes under the coastal plain is about 300 feet. From this it would appear that the peneplane surface was slightly upwarped along the southern edge of the coastal plain; but these irregularities in the present surface of the peneplane may well have been original. The peneplanation was by no means perfect. In some portions of the district no indications of its former existence are to be found. Between Barranquitas and Barros much of the country rises far above the peneplane level. Such an area can be regarded as a monadnock group. On the other hand, near Cidra, in the southeastern corner of the district, the general elevation of the country lies below the peneplane level. In this area the peneplane either was less uplifted originally or its original elevation has been entirely destroyed by subsequent erosion or warping. Indeed the present irregularities of the skyline and the variations in the general elevation of the upland surface are of such magnitude that the writer is forced to admit that the area may never have been peneplaned, and that the apparently even crestline that can be seen in parts of the district may be partly the result of an optical delusion on the part of the observer, and in part a real evenness, not necessarily caused by peneplanation, but due to weathering *in situ* and the formation of a thick soil mantle, which would tend to destroy the minor irregularities in the skyline.

ROCK FORMATIONS

The formational units of Porto Rico may be primarily divided into those that form the coastal plain and those that lie beneath it. These have been named the Younger and Older Series by Berkey. They are everywhere separated by a marked unconformity, so that they are entirely distinct structurally as well as lithologically and faunally. In the San Juan district the younger series includes all the formations encountered in passing from the coast to the inner lowland. These are, in the order of their respective ages, as follows:

1. The modern sand dunes of the coast and the adjoining playa plains.
2. The Pleistocene (?) San Juan lime sand.
3. The Oligocene limestones and shaly limestones (Arecibo formation).
4. The San Sebastian shales, developed near Lares, but not in the San Juan district. Probably Upper Eocene or lower Oligocene in age.

A detailed subdivision of the younger series will, no doubt, be possible when its fauna has been studied with care. The Arecibo formation is essentially a unit, though somewhat complex, and showing considerable variation laterally. The lower shale member is evidently a separate formational unit, merely representing a local development, which is not found in the San Juan district. A subdivision of the underlying older series, however, is quite another matter. The complexity of the formations and their lateral variations are so great that nothing more than a general subdivision will probably ever be possible. The local development of many of the formations, together with their disturbance and alteration by igneous agencies, make even the most generalized correlations largely conjectural.

Younger Series

RECENT DEPOSITS

Unconsolidated Lime Sand.—The modern dune sand, the occurrence of which as a narrow belt along the coast has been mentioned, consists of shell and coral fragments with occasional grains of quartz. Its constituents are almost identical with those of the associated consolidated deposits—a fact which leads one to infer that this sand is but a modern representative of the older consolidated San Juan sand. The belt of modern sand dunes is usually narrow, its greatest elevation of 8–10 feet being reached within 75 yards of the coast; from this point it slopes gradually inland and merges into the adjoining playa plains.

Playa Plains.—The playa plains, which occur as an east-west belt across the district, lying immediately south of the dune district, are partly fluvial and partly marine in origin. They are composed of material derived from the interior of the island through the ordinary processes of stream erosion and deposited by the streams passing out of the mountainous interior upon the comparatively level coastal plain.

These streams are now slightly entrenched, giving occasional exposures of a few feet in thickness. Such exposures show typical torrential bedding and deposits of fluvial character; however, marine shells are occasionally found upon the playas. These can be accounted for through temporary inundations. During the hurricane of August, 1898, practically the entire expanse of the playa plains of the district was flooded. At this time the simultaneous occurrence of heavy rains and strong northeast gale caused the inundation. It is evident, moreover, that the sea has not had direct access to the plains since the consolidation of the San Juan sand. Indeed the formation of an offshore sand bar in Pleistocene time may have been the controlling factor in the formation of the playa plains. In the sheltered lagoons formed behind the bar the alluvial material may have been deposited and subsequently uplifted with the San Juan formation. This would account for the typical fluvial appearance of the deposits, as well as their occasional evidences of the action of marine agencies.

PLEISTOCENE (?) DEPOSITS

San Juan Formation.—This name has been given by Berkey to designate the formation upon which the city of San Juan is built. It here forms a striking promontory that extends as a spit several miles out from the adjoining mainland and at its extremity attains an altitude of almost a hundred feet. This maximum elevation is crowned by the picturesque El Morro, the massive walls of the castle being built upon the very edge of the steep seaward face of the promontory (Fig. 8).

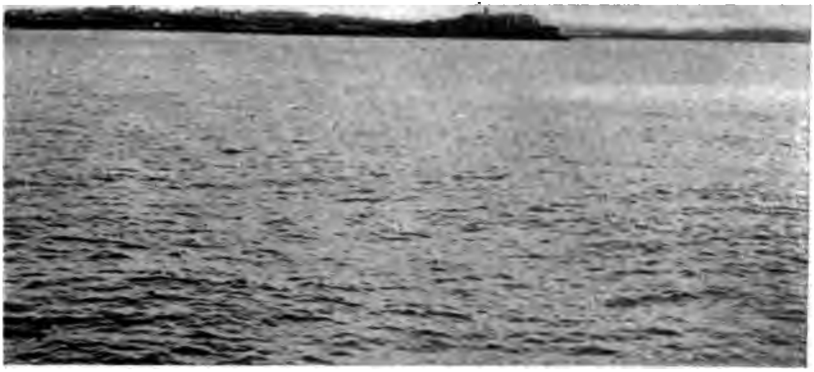


FIG. 8.—*Morro castle and a portion of the city of San Juan, built upon a promontory composed of the San Juan consolidated lime sand*

Photographed by H. E. Crampton.

The San Juan formation as seen at this point is a very porous, medium to coarse grained sandstone composed of minute fragments of shells and well-rounded quartz grains, bound together with calcareous cement (Fig. 9). The calcareous grains predominate and in some localities form practically the whole of the rock, so that the formation is essentially a lime sand. In other localities the quartz content is higher, but in no case did it constitute as much as fifty per cent of the rock. In the vicinity of San Juan two distinct types of the formation were found. First, that which occurs well above sea level near Morro Castle. At this point the lime sand is exceedingly porous. The cementing material does not fill all the interstices, the grains being cemented only at the actual points of contact. This mode of cementation has created a rock in which the volume of the pore spaces is about 20–30 per cent of the entire rock. The second variety of lime sand was taken from a quarry near Borinquen Park, about three miles east of the first locality. The material from this quarry, coming from below sea level, is dense and closely cemented, being locally used as a building stone. It is evident, therefore, that the degree of cementation is dependent upon the length of time the formation has been exposed to the free circulation of calcareous solutions. The upper portion of the formation, being re-elevated after only a short period of submergence, now shows only the initial stages of consolidation, while the lower portion, still submerged, has consolidated into a dense and very durable rock. The question then arises whether the porosity of the upper portion of the formation is not due to subsequent leaching rather than to

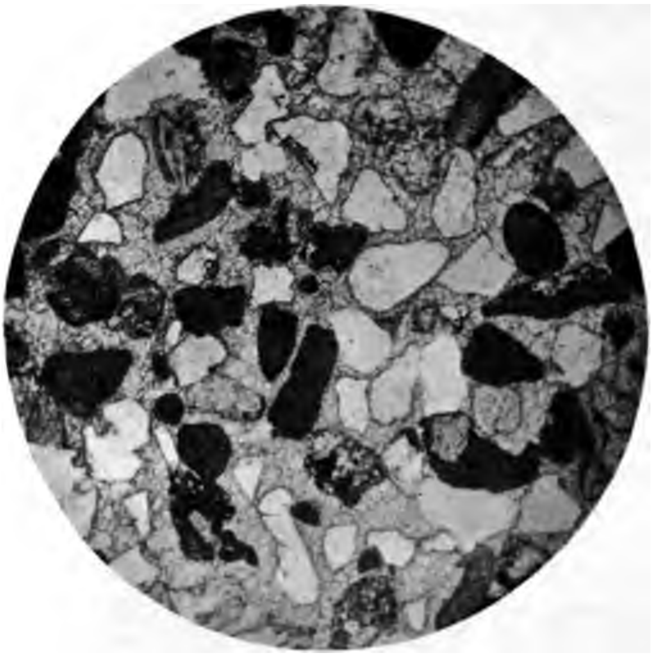


FIG. 9.—*San Juan consolidated lime sand*

initial poor cementation. A microscopic examination of the lime sand, however, shows no evidence of any appreciable amount of subsequent leaching, for a subsequent dissolution would have affected the readily dissolved calcareous fragments as well as the calcareous binding material.

West of the extremity of the San Juan spit, the continuation of the San Juan formation can be traced by a series of islands, the largest of which, Cabras, rises just in the center of the harbor entrance. Small fringing islands of this type, wholly composed of the consolidated lime sand, can be traced along the coast far beyond the western boundary of the district. All the headlands and points that rise above the general level of the coast are likewise composed of this material. Throughout this entire area one finds that the lime sand is characterized by very pronounced cross-bedding of an eolian type. This cross-bedding character is well shown in the face of the promontory below Morro Castle, as well as in numerous other localities to the west. The eolian type of cross-bedding, together with the fact that the San Juan lime sand is almost everywhere associated with modern dune sands, indicates that it was formerly of similar character to the modern dune sands, merely having been subsequently consolidated.

Age.—The exact age of the San Juan formation is uncertain. None of the modern sand dunes shows even the initial stages of consolidation. Indeed, much of the material composing them appears to have been derived from the destruction of the San Juan formation. Moreover, evidence of the final oscillations of the coast is clearly seen in the cliffs of this formation. Large portions of the consolidated sand still remain beneath the sea, so it is evident that the formation was formed before these coastal movements occurred. The formation contains no conclusive faunal evidence of its age. The shell fragments are so minute that none could be determined. Occasional foraminifera occur, but these proved valueless as an index of the age. The formation has been regarded by Berkey as being of Pleistocene age. This conclusion is derived from its general appearance, situation, and close association with modern dune sands of similar composition. Indeed, the upper portion of the formation might possibly be post-Pleistocene in age, though as yet no direct evidence has been found to support this view.

TERTIARY LIMESTONE SERIES

Arecibo Formation.—Underlying the San Juan formation, but separated from it by an extensive erosion interval, is the Arecibo formation, so called by Berkey from its type locality, the town of Arecibo. The formation consists of a series of reef and shell limestones alternating with layers of calcareous shale. Towards the base of the series the shales become predominant. In the vicinity of San Sebastian, in the northwestern part of the island, there is locally developed beneath the Arecibo formation a series of dark, lignitic shales, quite different from the yellowish, calcareous shales that occur in the base of the Arecibo in the San Juan district. No equivalent of these shales could be found in the San Juan district. It is the writer's opinion that the San Sebastian shale is merely a local development, which is not equivalent to the Arecibo, probably being much younger in age (see discussion of age of younger series). At Juana Diaz, on the southern coast, a similar shale member is to be seen. At this point, however, the beds dip as steeply as 36°, according to Berkey (1915, p. 13), which would seem to indicate either that they underlie the Arecibo unconformably or that they have been tilted by later movements. In the San Juan district the Arecibo formation dips 6° to the north. Its maximum thickness is not developed, but towards the western boundary it is at least 500 feet thick. It extends entirely across the district, forming a belt several miles broad on the west, but wedging to a mere line of isolated hills to the east. Much of its former extent has, no doubt, been destroyed by erosion, but it still covers an area many times larger than that occupied by any other single formation.

Along the valley of the Plata, where a good section of the formation can be seen, it consists, in the upper part, of a series of white reef and shell limestones of medium density, with occasional layers of yellow, impure, shaly limestone. The shaly layers increase in number and become essentially light-colored calcareous shales towards the base. The basal shales are of this character in this locality, and are entirely unlike the dark lignitic shales of the San Sebastian region. East of the Plata Valley the base of the formation is not exposed, but there is no evidence that its basal shales differ in composition from those seen in the Plata Valley. The Arecibo formation as a whole appears to be a structural unit. Although it is not uniform in character and composition throughout its vertical extent, yet there are no unconformities or erosional breaks, nor are the variations in general appearance distinct enough to warrant a closer subdivision. Since the formation varies laterally as well as vertically, no specified section would hold true for the entire district, yet as one passes over the formation certain general changes are observable, which are continuous throughout the district. The upper part of the series, as has been noted, is characterized by the predominance of a white or pinkish, chalky, poorly bedded limestone, partly composed of shells. Locally this limestone assumes a hard, dense, and massive character, being quite brittle and ringing when struck by a hammer. It is in this phase of the limestone that the caves, which are so numerous through the limestone belt, are developed. The absence of shaly material makes it readily soluble by underground waters. Locally the upper purer limestones show the characteristics and content of a coral reef. Near Morovis the limestone has such an appearance. Close examination shows that it is composed almost entirely of corals and is even more irregular and massive in structure than the white, chalky limestone. On passing downward through the series, one notes that the bedding becomes better defined and occasional layers of shaly limestone are to be seen. Thin, shaly layers occur even in the highest beds, but they do not become noticeable until better developed towards the base. In the lower portion of the formation the shaly layers become predominant and the massive, purer limestone is entirely lacking. The base of the series is entirely composed of calcareous shales, which are porous, coarse-grained, and well bedded. Such a succession would naturally be expected under the conditions which seem to have prevailed. After submergence the coarser, shaly material would be laid down first near shore, followed by finer shales and shaly limestones, with occasional beds of purer limestone marking temporary periods of clearer waters. Finally, the upper limestone beds and coral reefs would be deposited when clear-water conditions had been established.

Age.—The fauna of the Arecibo formation has never been carefully studied. The fossils are as a rule poorly preserved, nothing remaining but the internal molds which are rarely determinable. The older series was formerly thought to be Paleozoic, but the limestones of the coastal plain were early recognized to be of Tertiary age.

In 1868 Cleve (1883, p. 189) first approximately determined the true age of the older and younger series. He stated "that the island of Porto Rico consists largely of very thick, almost undisturbed limestone beds of Miocene age; but in the interior of the country, around Utuado, rocks similar to the Cretaceous of the Virgin Islands are met with."

In 1898, after a reconnoissance of the island, Hill concluded that the ages of the Tertiary formation were as follows (Hill, 1899*a*, p. 109):

> The upper part of the Pepino hills is made up at their surface of a rather hard lime marl full of coralheads, with occasional indurated strata of firm white porous limestones. These rocks (the Pepino formation) are of Miocene age, as determined by Mr. T. Wayland Vaughan from the corals collected by me, similar to certain rocks of Antigua hitherto not known in the geologic sequence of the Greater Antilles. Their tilted position, standing at 1200 feet where they meet the older volcanic mass, testifies to the great geologic movements which have taken place in the West Indies in late geologic time.
>
> Below this limestone, which is at least 100 feet thick, are fossiliferous

greensand marls of undetermined age (Eocene or Oligocene), which in turn rest upon a great thickness of thinly stratified reddish lignitic clays and sands of Eocene age (the Richmond formation) which outcrop near San Sebastian, Guatemala and Mocha on the western end of the island, and near Carolina on the northeast coast.

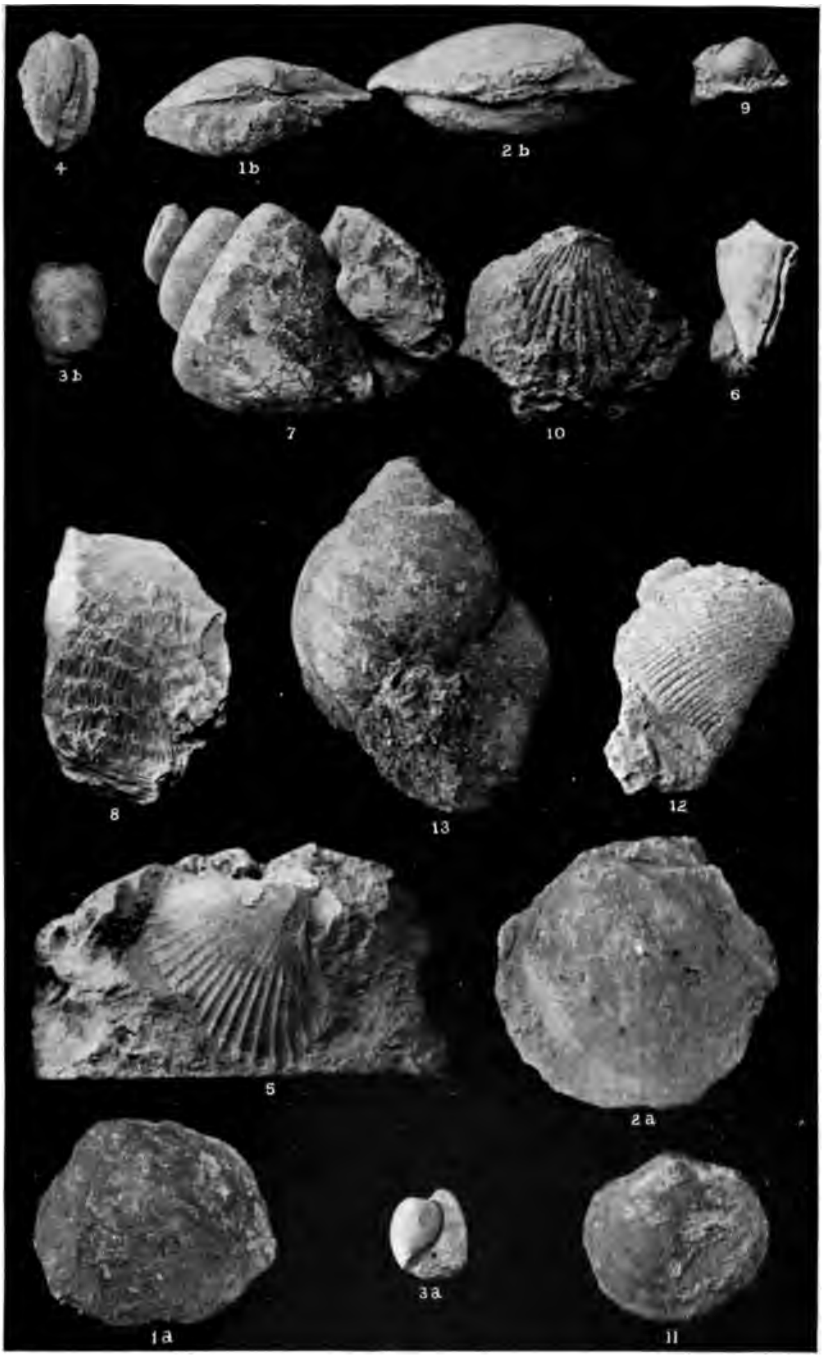
The *pepino* formation is in part equivalent to the Arecibo. No greensand marls were found in the San Juan district, but these probably correspond to the lower shaly Arecibo. The lignitic clays and sands are what has since been termed the San Sebastian shales. In the older limestone beds of the interior, Hill mentions the occurrence of a Cretaceous fossil (Rudistes), thus confirming Cleve's earlier supposition that the older series was of Cretaceous age.

Through the aid of Dr. William H. Dall, the material which the writer collected in the San Juan district, as well as some of that collected by Dr. Berkey the summer previous, was roughly determined. The material consisted almost entirely of internal molds, some of them being so poorly preserved that even the genus could not be determined. In only one case was a species positively identified, but the accumulation of evidence from quite a number of genera, as well as the general appearance of the forms, made the determination of the ages of the respective members of this series fairly reliable. The forms studied should be divided, according to the locality from which they were collected, into three groups:

1. Collected by the writer from the base of the Arecibo, near Toa Alta and from the upper part of the same formation near Vega Baja. The forms from these two localities are so much alike that no attempt was made to distinguish between them.
2. Collected by Berkey from the Ponce formation just northwest of Ponce, on the southern coast.
3. Collected by Berkey from the San Sebastian shales (upper portion) near Lares.

The fauna from the Arecibo formation consisted of pelecypods, gastropods, and corals, of which the following genera were identified:

Metris trinitaria (Dall), an index of the Bowden formation, upper Oligocene of Jamaica, found throughout the Arecibo formation in the San Juan district (Pl. II, 1*a*, 1*b*).
Pecten sp. (Pl. II, 5).
Mittha sp. (Pl. II, 2*a*, 2*b*).
Haminea sp. Very abundant (Pl. II, 3*a*, 3*b*).
Cypræa sp. Abundant (Pl. II, 4).
Amauropsis sp.
Conus sp. (Pl. II, 6).
Ampulina sp.



FAUNA OF THE ARECIBO FORMATION

Strombus sp. (Pl. II, 7).
Orbicella aff. cavernosa (Linn.).
Fungid coral, not determinable, but similar to those found in the Oligocene of Antigua, Anguilla and Cuba (Pl. II, 8).
Venus sp. (Pl. II, 9).

Although only the first of these forms may be regarded as even an approximate index, yet the fauna as a whole from its general appearance is regarded by Dall as Upper Oligocene. The occurrence of *Metris trinitaria* at the base as well as in the upper portion of the formation would indicate that the entire Arecibo formation as developed in the San Juan district is Upper Oligocene.

The second group of fossils was collected from the Ponce formation on the southern coast. This material was also so poorly preserved that the genus could not always be determined. This group includes:

Lucina sp.
Lucina sp. small specimens much like forms from the Chattahoochee (Middle Oligocene of the Gulf Coast). (Pl. II, 11.)
Pecten sp. like *P. thetidis* (Sowerby). (Pl. II, 10.)
Fasciolaria (Pl. II, 12).
Amauropsis ocalana (?) similar forms in Ocala limestone, Vicksburg formation, lower Oligocene of the Gulf Coast (Pl. II, 13).

As the relative position of the specimens in the Ponce formation was unknown, the geologic range could not be determined. It is probable that the specimens were collected from the lower portions of the formation. These forms at least indicate that the formation is lower to middle Oligocene and that it is in part practically equivalent to the Arecibo formation of the northern coast.

The third group was collected near Lares from the first shell bed of the San Sebastian shales. This shell bed is located in the upper portion of the shales. It contained:

Venericardia sp.
Ostrea sp.
Conus sp.

None of the forms of this group could be used as an index of its age, but from their general appearance Dall concluded that they were lower Oligocene or possibly upper Eocene. Therefore, since these forms were collected from the upper part of the San Sebastian shales, it is probable that these shales are, in greater part, of lower Oligocene age.

OLDER SERIES

Underlying the Arecibo formation is a complex series of sediments of both aqueous and volcanic origin, intimately associated with numerous igneous rocks. It is this complex that Berkey has termed the older series, since it is unconformably separated from all the formations that have been described and is in appearance much older than these strata. The older series outcrops in all parts of the San Juan district south of the inner lowland, an areal extent of roughly two-thirds that of the whole district. The contrast in appearance of the two series is strikingly evident as one passes abruptly from the nearly horizontal beds of the Arecibo formation, showing comparatively simple structure and only minor variations in lateral and vertical extent, to the steeply tilted beds of the older series, where sediments and volcanics of all varieties are dissected by an infinite number of igneous rocks, both intrusive and extrusive, ranging in size from small stringers to major intrusives of many square miles in extent. The subdivision of this intricate series is an exceedingly difficult task. Many of the formations are of such insignificant thickness that they would necessarily have to be grouped to appear on a geologic map of moderate scale. Such grouping would be on an arbitrary basis, for the formations involved do not naturally fall into larger groups. Consequently, only generalized subdivisions have been made on the geologic map, the detail in structure and composition being shown on the accompanying cross-sections (Pl. IV). The rocks of the older series include:

Sediments essentially marine.
Sediments essentially volcanic.
Igneous rocks.

Marine sediments which have been wholly derived from the land through the ordinary processes of erosion and stream transportation are almost unknown in the older series of the district. Practically all of the marine sediments contain volcanic material. Some are composed wholly of volcanic material cemented by carbonates. These sediments have been well assorted and bedded, and often contain marine organisms. The marine sediments—that is, those that show more strongly the characteristics of marine rather than those of volcanic sediments—include limestones, shales, sandstones, and conglomerates. These form only a small percentage of the total thickness of the older series. Occasionally shale and conglomerate beds of 100 yards or more in thickness are to be seen, but the limestone beds are usually less than 100 feet in thickness. With the marine sediments, the extended series of volcanic ashes and tuffs is intimately associated. The ash beds are usually well bedded and a certain degree of assortment can be seen in the material that has been either ejected directly into the sea or subsequently reworked. The tuffs are in greater part massive; others are well bedded and show evidence of marine assortment. The ejectmental material is of all sizes from fine ashes composed of grains less than .01 mm. in diameter to coarse tuffs containing fragments a foot or more in diameter. A continuous series is formed between these two extremes, so that the distinction between ashes and tuffs is merely an arbitrary one based on size of grain. The complexity of the older series is primarily due to large number of igneous rocks that occur closely associated with the sediments. But for the fact that the older series has been so thoroughly dissected by igneous intrusions, its correlation and geologic mapping would be a comparatively simple matter. As it is, however, correct mapping can only be done after detailed study of areas where outcrops are numerous.

RESIDUAL SOIL AND DEPTH OF DECAY

None of the rock formations of the district is free from surface alteration and decay. The older series, longer exposed to the weathering agencies, has been altered to considerable depths and is now almost everywhere covered by a residual soil locally reaching many feet in thickness. Its greatest development is in the inner lowland, where the relief is moderate and stream transportation slower. In this region it is often possible to make excavations of 15 feet in depth without encountering bed-rock. Consequently, in this lowland region outcrops are uncommon and the few that occur are often so highly decomposed that the exact nature of the original rock remains uncertain. Even in the mountainous region where outcrops are plentiful many of them are badly decomposed. The stream beds and recent road cuts afford the best opportunities for the study of extended surfaces of fresh rock. Even though the temperature changes are small, exfoliation is common, producing peculiar concentric arrangements that are strikingly prominent in many of the shales, volcanics, and igneous rocks (Fig. 10).

One of the most striking characteristics of the topography of the oldland is the remarkable stability of the soil mantle. As has already been noted, the soil mantle, remaining practically *in situ*, might well be regarded as an important factor in determining the regularity of the crest line, in many places giving rise to well rounded hill summits that have been regarded as good evidences of peneplanation. Hillsides that slope as steeply as 40° can be cultivated with little or no loss of soil. Knife-edge divides with 40° slopes on either side retain their soil to the very summit and can be ploughed without fear of washing, even after the heaviest rain. Berkey ascribes the causes of the stability of the soil mantle to three factors (1915, p. 35); first, the dense cover of vegetation; second, the small range in daily and annual temperature; and, third, the low content of inert or refractory material, such as quartz, in the rocks whose destruction has furnished the soil. Neither of the first two of these factors would explain the stability of the soil when unprotected, subsequent to cultivation. The third, however, is of vital significance. The igneous rocks as well as the volcanic material are predominantly of andesitic composition, contain large amounts of feldspars and ferromagnesian minerals, and little or no quartz. This on weathering would give rise to an argillaceous soil, essentially a clay, which would be very impervious. A soil of this character would not permit the free circulation of ground water and would not readily be removed and transported by the surface run-off.

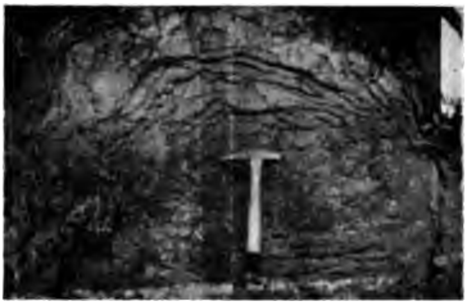


FIG. 10.—*Exfoliation producing concentric arrangements in ash beds south of Bayamon*

The presence of a widespread mantle of such impervious soil might well explain the peculiar absence of meteoric springs throughout the island. True springs are almost unknown in the San Juan district. The so-called springs are merely rivulets of surface water, hidden in their upper courses by dense vegetation. On the southern coast several thermal springs have been found, but it is now believed that these derive their water from magmatic rather than meteoric sources. Whether the imperviousness of the soil is the sole cause of the absence of springs is not yet determined, but it is at least a possible explanation of an otherwise unexplained phenomenon.

COROZAL LIMESTONE

Just southwest of the town of Corozal, as one crosses the river at the ford on the road to Barros, can be seen an outcrop of limestone. Close inspection shows that it is a dense, grayish, brittle rock, comparatively easily dissolved, as is indicated by the few outcrops that rise above the residual soil. Moreover, the limestone is strongly fragmental. It consists of angular limestone fragments, usually less than 2 inches in diameter, and occasional particles of feldspars or ferromagnesian minerals, thoroughly bound together by a calcareous cement. The strike of the bed is roughly N. W.–S. E. Its dip could not be accurately measured, as none of its structural relations could be determined from the few limited outcrops. The dip, however, was judged to be about 15°–20° N. E., since it was apparently conformable with the neighboring types which show approximately that dip. The thickness of the bed is also uncertain, but it is not believed to exceed 100 feet. This limestone can be followed from a mile southeast of Corozal until it plunges below the Tertiary strata to the northwest.

The origin of the fragmental structure, which is characteristic of this limestone, is quite puzzling. An examination of the rock under the microscope shows that the fragments are angular, indicating that they have undergone little or no transportation. Moreover, particles of feldspars and ferromagnesian minerals, which are perfectly fresh, occur with the limestone fragments, so one must also infer that consolidation took place very soon after deposition. It is the writer's belief that the fragmental structure in the limestone is directly due to volcanic agencies, that is, brecciation was caused by volcanic eruptions which probably took place as submarine eruptions through a limestone bed. The shattered limestone was then deposited with intermingled feldspars and ferromagnesian minerals, and the whole cemented by further precipitation of $CaCo_3$ from the sea. The presence of marine organisms in the interstitial $CaCo_3$ makes it evident that the breccia was at least reworked by the sea, and the angularity of the fragments would indicate that the ejectmental material was thrown directly into the sea, or that the eruption itself was submarine. Such an explanation for the origin of the Corozal limestone breccia is not without its defects. The breccia is of considerable extent, yet no traces of the older limestone beds, which were shattered to form the breccia, could be found. It is possible that the locality just south of Corozal, where the brecciated structure is best developed, marked the locus of the eruption, and that in other unexposed portions of the limestone bed the fragmental structure might be lacking. In this case the fragmental material would be practically *in situ*, forming only a brecciated phase in the original limestone bed. If such were the correct interpretation, however, one would expect the breccia to contain a large amount of volcanic material. In reality it is composed almost wholly of fragments of pure limestone, but it occurs closely associated with an extended series of bedded tuffs, indicative that the deposition of the limestone fragments occurred first, followed by that of the tuffaceous material. The Corozal limestone breccia contains abundant foraminifera, which will be described with the other foraminiferal beds under the discussion of the age of the older series.

LA MUDA LIMESTONE

Berkey (1915, p. 22) has described the occurrence of this limestone just east of the San Juan district near La Muda. The same limestone was found by the writer just south of the town of Guaynabo, where it is exposed in a small quarry as one leaves the town by the trail to La Muda. Its strike is N. 48° W. and dip 30° S. W. The thickness of the bed was roughly determined as about 40 feet at this point. To the east, according to Berkey, its thickness materially increases. The formation could be traced along its strike for a distance of about 5 miles. Northwest of Guaynabo it finally disappeared under the heavy residual soil of the inner lowland. To the southeast no outcrops could be found beyond K 26 on the military road. It possibly continues farther, as no careful search was made for it east of the San Juan district.

The Muda limestone shows a fragmental structure similar to that seen in the limestone near Corozal. It is not so striking, however, as that seen in the Corozal limestone, because of closer cementation of the fragmental material which gives rise to a dense, grayish-white limestone, in which the fragmental structure is only betrayed by its somewhat mottled appearance. Microscopic examination of the limestone shows the fragmental structure well defined, as well as small amounts of tuffaceous material and foraminifera scattered throughout the cementing material. The limestone, on the whole, is very similar to the one at Corozal and both, no doubt, have originated in the same manner. The Muda limestone is likewise closely associated with tuffaceous formations.

AGUAS BUENAS LIMESTONES

Two miles south of the town of Aguas Buenas are the great caves of Porto Rico (Dinwiddie, 1899). These are developed along the strike of a limestone bed about 100 feet in thickness. The strike of this bed is roughly N. 50° E. and dip 20° N. W. In the valley of the Bayamon River, to the west of the caves, two limestone beds are to be seen, which are apparently conformable. To the southwest the same beds may again be seen in the valley of the Arroyato River, so the strike was closely determined by plotting the outcrops. The strike of these limestone beds is practically normal to the general strike of the formations throughout most of the district. This pronounced variance in strike indicates that the Aguas Buenas limestone beds are unconformably related to the other beds of the older series. Above the thickest of these two limestones, in which the caves occur, is a coarse conglomeratic tuff which contains fragments of the older limestone. Beneath the limestone are other tuffs, or rather tuffaceous limestones, which resemble Muda limestone, except that they contain larger amounts of tuffaceous material. No foraminifera or other organisms by which the age of these formations could be determined were found, but from the structural relations it would be inferred that the Aguas Buenas limestones lie below and are unconformably separated from the limestones previously described. The structure of this area, however, was not satisfactorily worked out. If the area to the east of the San Juan district is eventually mapped, the relationship of the Aguas Buenas to the Guaynabo limestone may be made clear, for the former should be truncated by the latter in the valley of the Loisa River north of Caguas, provided each continues that distance along its line of strike.

LIMESTONE AT K 29

On the Comerio road, at K 29, a thin bed of impure limestone approximately 5 feet thick occurs interbedded with tuffs and ashes. The limestone contains a large amount of tuffaceous material, being in reality merely a tuff that has been highly carbonated. Although insignificant in size, this limestone bed serves as a typical illustration of the frequent occurrence of limestones partly of volcanic origin, occurring intimately associated with volcanic sediments. Impure limestones were also noted on the trail from Barros to Corozal and in the lower valley of the Barrancas River.

JUAN ASCENCIO CHERT BEDS

Northwest of the Aguas Buenas limestones in the barrio of Juan Ascencio there is a chert bed of considerable thickness, the strike of which is approximately parallel to the limestone beds (N. 50°–60° E.). The dip and thickness of the bed could not be determined from the few scattered outcrops that were found. This chert is a hard, dense, grayish white rock, which consists wholly of an exceedingly fine-grained aggregate of silica, showing an absence of any bedding. Just north of the ridge on which this chert outcrops a siliceous rock showing fine crumpling was discovered. A microscopical examination of this rock proved that it was essentially the same composition as the chert to the south, except that it was quite highly colored in the weathered outcrop by iron oxides. The first of these chert beds probably originated through the silicification of some sedimentary bed, either a limestone or a calcareous shale. The second chert is either a phase of the same formation or a different one, which slumped before solidification. Subsequently the formation was silicified, the intense crumpling due to solifluction being preserved in the secondarily formed chert. Still later, the iron content of the chert has been oxidized to limonite and hematite which occur in bands following the crumples, thus serving to emphasize the intensity of the crumpled structure (Fig. 11).

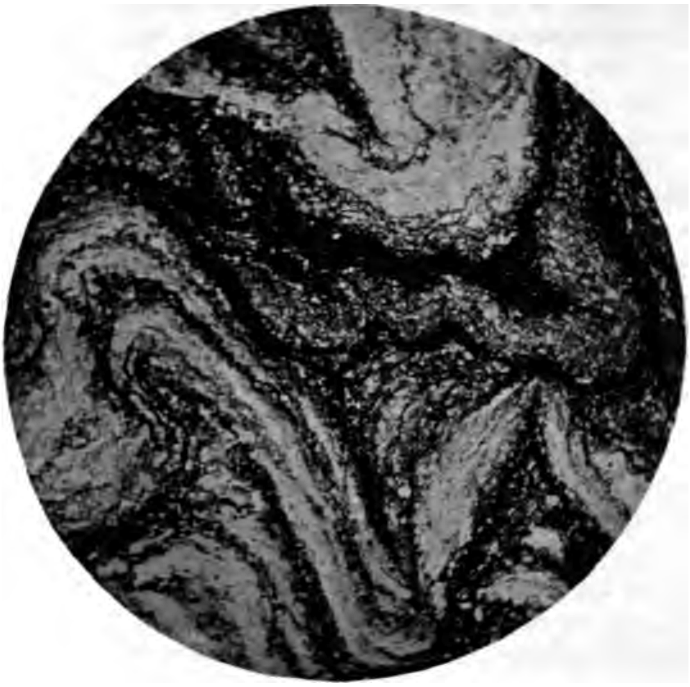


FIG. 11.—*Crumpling due to solifluction in the Juan Ascencio chert*

COROZAL JASPER BED

A bed 10 feet thick of Jasper was found in the Corozal River two miles above the town. Only one outcrop was located, from which it appeared that the bed was conformable with the surrounding formations. From the amount of jasper float found in the streams it was inferred that the bed was of considerable extent.

SHALES

One might conclude from a hurried examination of the island that shales are commonly encountered in great extent, but in reality typical shales are only occasionally found. Many of the formations that have been recorded as shales are well-bedded ashes. Indeed, such a gradation exists between the shales and ashes that in some cases one cannot be sure in just which class a given formation belongs. All the shales found in the San Juan district contain some volcanic material. Many of them are composed almost wholly of ashy material. The intimate association of shales and ashes would lead one to infer that either might have been deposited under essentially the same physical conditions, that is, the change from shale to ash accumulation need not mark any noticeable change in the climatic or physical conditions under which they were deposited. Many of the shales are calcareous. Some contain such large quantities of calcareous material that they have formerly been regarded as limestones. Foraminiferal shells occur in some of the shales and occasionally a shale is almost entirely composed of these minute organisms.

The largest accumulation of shale in the district is near the town of Barranquitas, where the aggregate thickness of the shale series must be several thousand feet. These shales are very calcareous, so much so that they were originally regarded as limestones by Hill (1899, p. 108). They represent the calcareous extreme in the shale series, but strictly speaking they should not be termed limestone. The shales extend from about K 40 on the Comerio-Barranquitas road to a point a good distance south of Barranquitas on the road to Aibonito. They form the crest of the island in this vicinity, extending down some distance on either side of the principal divide. The shales contain a good deal of ashy and tuffaceous material and are locally interbedded with ashes and tuffs. The strike of this series is roughly N. W.–S. E., which indicates that it is now simply a phase in the extended series of tuffs and ashes that form the basis of the island.

On the Bayamon-Comerio road, at K 5, there is an outcrop of well stratified shales dipping 45° to the S. W. and apparently striking parallel to the general N. W.–S. E. strike of the region. Fresh specimens can be obtained in the road cut, which when examined under the microscope show an exceedingly fine-grained texture. The material is in such a fine state of subdivision that nothing can be recognized except minute grains of quartz. The rock is very dense, with little or no pore space. Faint banding can be discerned in the hand specimen, but no orientation or bedding is visible under the microscope. Berkey has suggested that these shales may be equivalent to those exposed at Mayaguez and Fajardo. The material from Fajardo, however, is quite different in appearance. It is a light, porous shale, the porosity of which is due to numerous minute cavities which apparently were previously occupied by foraminiferal shells. The leaching of these calcareous organisms has produced a porous structure which is not to be found in the dense shales exposed at K 5. It is possible that this shale may be equivalent to those exposed at Fajardo and Mayaguez, but the writer does not believe that correlation of such widely separated formations can yet be made with any degree of certainty.

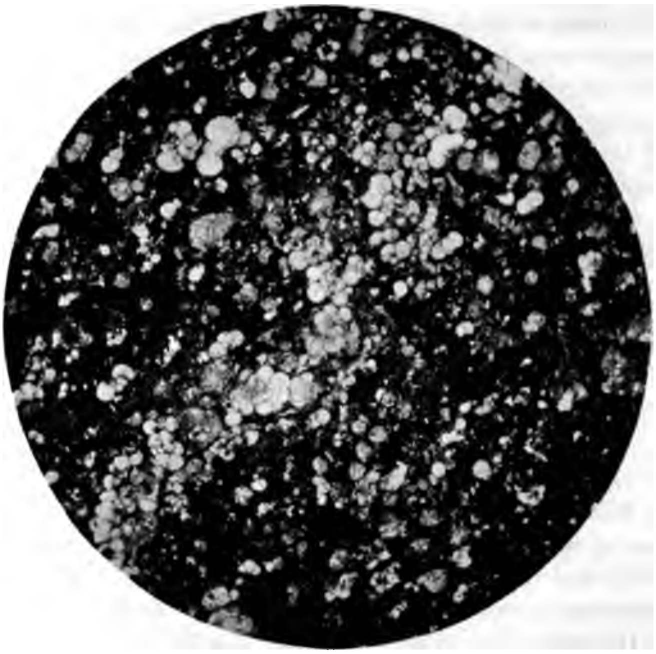


FIG. 12.—*Typical foraminiferal shale*

In a road metal quarry just off the Comerio road, at K 8, there is an exposure of sandstone with included fragments of shale. The shale is dark, dense, and very fine-textured. Its occurrence as angular fragments in the sandstone leads one to infer that it has undergone much the same process of formation as the Corozal limestone breccia. This shale occurrence is insignificant in size, but it is of great interest in that it contains numerous foraminifera, which not only indicate the conditions under which it was deposited, but also give an idea of its age (Fig. 12). The foraminifera will be described in the discussion of the age of the older series.

A somewhat extensive series of shales was discovered in barrio Piñas, southeast of Toa Alta. These shales are well stratified. Their strike is about N. W.–S. E. and dip 20° S. W. On the weathered outcrop the shale appears as a light, porous rock, which is composed of an aggregate of very fine, shaly material with numerous minute cavities, some of which are now filled with quartz and zeolites. These cavities were in part at least originally occupied by foraminiferal shells, which have been leached out and the cavities in part refilled with quartz and zeolites. A large percentage of them, however, is still empty and as a result the shale is exceptionally porous. This shale is very similar to a specimen collected by Berkey from Fajardo, but as yet too little is known about either of the formations to attempt any correlation.

Another shale of similar character occurs in barrio Cuchilla, where the Morovis trail crosses the Unibon River. The shale strikes N. W.–S. E. and dips 30° to the N. E. It contains a great deal of ashy material, together with numerous foraminifera. The formation might equally well be described as a volcanic ash series that has been thoroughly reworked and assorted by the sea.

SANDSTONES

Pure quartz sandstones are almost unknown in Porto Rico. This is due to the fact that so few of the rocks contain quartz in any appreciable quantity. Only the granites and rhyolites, which are comparatively rare in the San Juan district, could afford a source of quartz sand, so it is not surprising that quartz occurs only as an unessential constituent of the sandstone formations. The few sandstones that are found in the district are composed chiefly of tuffaceous material that has been well sorted and somewhat rounded by stream and wave action.

The most interesting occurrence of sandstone that was found is to be seen in the quarry at K 8 on the Comerio road. It is a dense, medium-grained, dark greenish rock showing good bedding and containing numerous inclusions of shales. The formation dips 42° to the S. E. and apparently strikes N. 65° E. This is nearly normal to the general strike of the district, and agrees more closely to the limestones south of Aguas Buenas than with the conglomerates and tuffs just to the south. It is the writer's opinion that this sandstone is of limited extent, representing an ancient delta or fan. Such a theory of its origin would explain its abnormal strike. The sandstone is composed of a granular aggregate of ferromagnesian minerals, feldspars, and occasional grains of quartz. This material is undoubtedly of volcanic origin. In other words, this sandstone is merely a fine-grained tuff, the constituents of which have been somewhat rounded and assorted in being transported from the point of eruption to the point of accumulation. The angularity of many of the grains, and especially of the shaly fragments, leads one to infer that the material has not undergone extended transportation.

In barrio Padilla, where the Corozal-Morovis trail crosses Piedras Muellas Creek, there is an interesting occurrence of arkose sandstone. The sandstone is a medium to coarse-grained, greenish rock, consisting of an aggregate of feldspar and quartz grains with interstitial chlorite. The feldspar grains, which are predominantly plagioclase, are somewhat murky, but no actual decomposition has yet set in. This sandstone also is essentially a volcanic tuff. The presence of such a large percentage of unaltered and angular feldspar grains indicates that the material was deposited almost at its source.

A fine-grained, reddish quartzite was discovered in barrio Santa Olaya, just south of Helechal Peak. This was the only sedimentary rock found in the district that consists chiefly of quartz. It appears to have been first deposited as a fairly pure quartz sand. Later this sandstone was further silicified, probably under some degree of pressure, as a faint orientation of the grains can now be seen. The quartzite apparently does not represent the product of regional or contact metamorphism, but is merely a highly silicified sandstone.

CONGLOMERATES

Conglomerate beds are frequently found in the older series. In aggregate they form a large percentage of its total thickness. They are, however, much more abundant on the southern than on the northern side of the island. The conglomerates occur in belts trending N. W.–S. E. or parallel to the major tuff series, which apparently form the backbone of the island. It has been suggested that the conglomerate belts represent breaks in the older series, separating it into disconformable or possibly unconformable groups.

The only important conglomerate that was found in the San Juan district can be best seen in the cuts along the Comerio road at K 12-13. This is a boulder conglomerate, which must be over 500 feet thick, though there are not enough outcrops to determine its exact thickness. Its strike is about N. W.–S. E. The material of which this conglomerate is composed is almost entirely volcanic in origin. The boulders are chiefly igneous rocks, especially andesite porphyries. Occasional boulders of older tuffs were also found. It is possible that this conglomerate was formed by the erosion of some older tuff formation, but it is more probable that it represents an accumulation of tuffaceous material directly derived from volcanic sources, and rounded by stream action during transportation to its point of deposition. This view is supported by the fact that the material is exceedingly poorly assorted. Large boulders and very fine tuffaceous material are intermingled in all proportions. If this conglomerate were produced through the ordinary agencies of stream erosion, some assortment of the material would be expected.

The conglomerates are in many places closely associated with igneous activity. At K 12.5 on the Comerio road a felsitic dike, 10 feet thick, intrudes the conglomerate (Fig. 11). At other points it is intruded by larger igneous bodies. Northwest of Aguas Buenas, in the bed of the Bayamon River, there is a conglomerate which appears to have been saturated by the still molten magma, for boulders can now be seen in a crystalline matrix. The phenomenon has been reported by Berkey as occurring in some of the conglomerates on the southern side of the island. The extensive series of Muda tuffs also shows conglomeratic phases, but as this formation is essentially a tuff, it will be described below under that head.

TUFFS

The conglomerate formations in many places grade imperceptibly into bedded and massive tuffs, which constitute the most abundant rock type that is found on the island. They occur in an extensive series of great variety, forming the most dominant structural feature of the older series. The tuffs for the most part are massive in structural habit. Bedded tuffs, however, are frequently encountered which have been worked over and somewhat assorted during deposition. The finer material shows better bedded structure, and the finest ashy material is often perfectly bedded.

The tuffaceous material shows a good deal of variety in composition. For the most part, however, they are composed of fragments of igneous rocks, predominantly the porphyritic andesitic type, so that this variety may be termed andesitic tuffs; yet a close examination of a large amount of the volcanic material reveals the fact that practically all the rock types of the older series are represented. Fragments of all the important igneous rock types were found, as well as occasional fragments of older tuffs. At K 7.5, on the Comerio road, a tuff containing numerous fragments of limestone was found. The limestone fragments are dissolved out on the weathered surface, giving the tuff a pitted aspect. Near this point is the tuffaceous sandstone which contains large fragments of shale. It is evident, therefore, that the tuffaceous material, though of general andesitic composition, contains a large variety of rock types of different composition, some of which locally constitute large portions of the entire tuff formation.

The composition of the tuffs is often locally modified by the intrusion of igneous rocks. The cutting of tuffs by igneous dikes and larger intrusions usually has little effect upon them, but it often happens that the magma, while still molten, has permeated the tuff and there crystallized, forming a tuff with a crystalline matrix. In consequence, it is often exceedingly difficult to distinguish between a tuff that has been invaded by an igneous magma and a true intrusive igneous body that contains numerous inclusions.

The tuffaceous rocks are especially liable to alteration and modification. As they are usually poorly consolidated when first deposited, they form mediums readily permeated by aqueous solutions of all kinds. Consequently, many of the tuffs have been so highly altered that their original structure is almost wholly obscured. The commonest process that has modified the tuffaceous rocks is a thorough silicification, which changes the formerly non-resistant tuff to an indurated, exceedingly resistant rock. Silicified tuffs of this character underlie the most pronounced topographic features of the island. In the San Juan district it was noted that they formed both Torrecilla and Helechal peaks, the two most prominent features in the topography of the whole district. The latter peak rises abruptly from a rolling surface of about 500–800 feet in altitude to the height of 1800 feet.

It would be impractical to describe individually the numerous tuffaceous formations of the district. They occur in N. W.–S. E. belts and are especially well developed in the southwest portion of the district. In this region they form practically all the country rock, with the exception of the tuffaceous shales and igneous intrusives. An excellent development of tuffs can be seen along the entire stretch of road from Barranquitas to Barros. In the vicinity of Comerio they are also well developed. The Muda tuffs represent the most extensive series found in the northeastern portion of the district. These also strike N. W.–S. E. and their aggregate thickness is probably several thousand feet. They are well exposed in the bed of the Guaynabo River, and also along the Guaynabo-Muda-Aguas Buenas trail.

AGE

The distinctly older appearance of the older series, as well as its highly tilted position, leads one to infer that an erosion interval of some magnitude separated it from the overlying coastal plain. Moreover, the evidence of extraordinary igneous activity throughout the deposition of the older series and its complete absence in all the subsequent formations indicate either an extended time interval or a rather sudden change in physical conditions. It was the consideration of these points that led the first observers to regard the older series as probably Paleozoic in age. This idea, however, was soon abandoned; for, as above noted, Cleve, in 1868, suggested that the formations of the older series much resembled the Cretaceous of the neighboring islands. Hill later confirmed this view by the discovery of the Cretaceous fossil Rudistes in a grayish limestone bed that strikes from Cabo Rojo eastward to about 15 kilometers north of Ponce on the Adjuntas road.

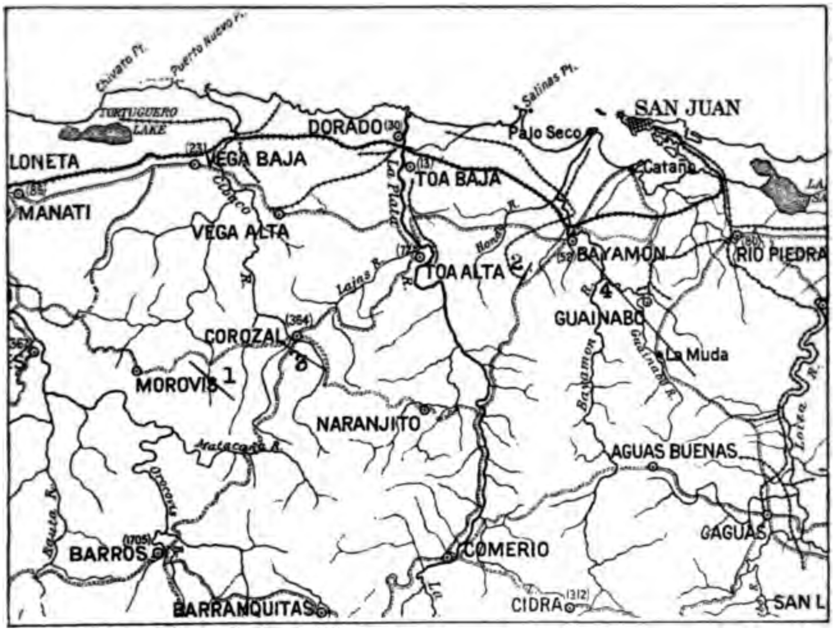


FIG. 13.—*Chart showing the relative positions of the principal foraminiferal beds*

1. Unibon shale.
2. Shale inclusions in the sandstone at K 8. Comerio Road.
3. Corozal limestone.
4. Muda limestone.

The formations of the older series of the San Juan district are, with the exception of certain foraminifera, almost universally unfossiliferous. The few other forms that have been found come without exception from the southern side of the island. In the upper part of the series, in the San Juan district, the beds of foraminiferal shales and limestones which have been mentioned serve to throw some light on the age of the series.

On the accompanying chart (Fig. 13) the four most important of these formations have been indicated numerically:

1. *Unibon shale*, at juncture of the Morovis trail and Unibon River. Strike, N. W.–S. E. Dip. 30° N. E.

2. *Shale* fragments in *sandstone at K 8*, Comerio road. Strike, N. 65° E. Dip. 42° S. E.

3. *Corozal limestone breccia.* Strike, N. W.–S. E. Dip. 15–20° N. E. (?).

4. *Muda limestone.* Strike, N. W.–S. E. Dip, 30° S. W.

The Unibon shales show typical chalk foraminifera (Upper Cretaceous). Since only sections of the forms are obtainable, it was often impossible definitely to determine the species. Through the assistance of Dr. R. M. Bagg, of Appleton, Wisconsin, the writer was able to recognize a sufficient number to leave little doubt as to the age of the formation. The following forms were identified:

Globigerina cretacea, d'Orbigny[3] (Pl. III, 1).
Globigerina bulloides, d'Orbigny.[4]
Truncatulina lobatula, Walker and Jacob[5] (Pl. III, 2).
Nodosaria communis, d'Orbigny[6] (Pl. III, 4).
Nodosaria farcimen, Soldani.[7]
Textularia sp.

While none of these forms is a conclusive index of the chalk horizon, yet considering their abundance and general aspect, they could hardly be regarded older than Upper Cretaceous.

A foraminiferal fauna very similar to this was found in the shale at K 8. Its forms are even more like those characteristic of the English chalks. This fauna comprises:

Globigerina cretacea
Globigerina bulloides
Orbulina universa
Truncatulina lobatula
Textularia globulosa (Pl. III, 3)
and a few Rotaline forms.

The foraminifera of the two limestone beds are essentially the same. They are characterized by numerous Miliolidæ, as well as Rotaline and Textularia-like forms. In these limestones were found:

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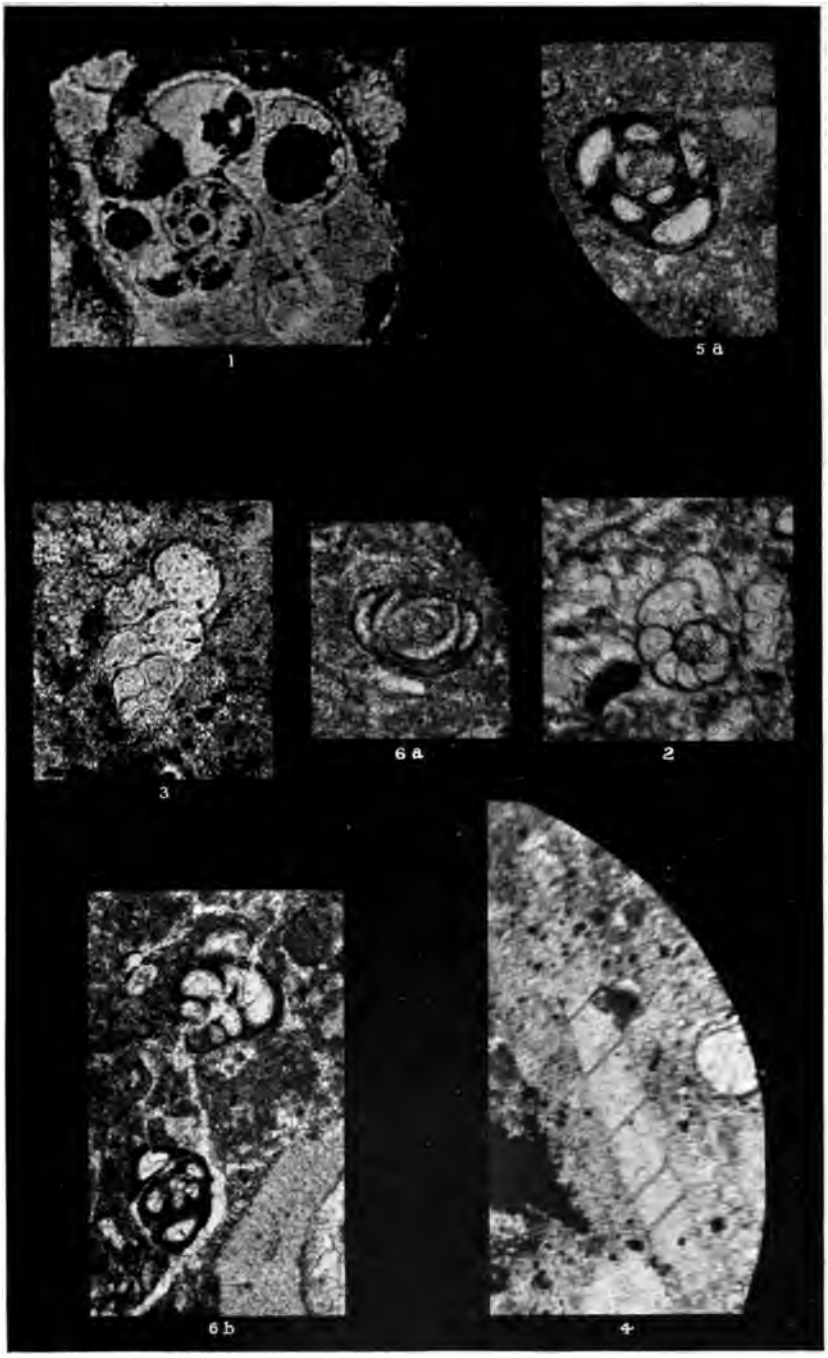
[3] Report of *Challenger* Expedition. IX, p. 596, Pl. LXXXII, 11*a-c*.

[4] Op. cit., p. 593, Pl. LXXIX, 1-7.

[5] Op. cit., p. 660, Pls. XCII, 10; XCIII, 1, 4, 5.

[6] Op. cit., p. 504, Pl. LXII, 9-20.

[7] Op. cit., p. 498, Pl. LXII, 17-18.



FORAMINIFERA

Miliolina seminulum, Linné (Pl. III, 5*a*, 6*a*, 6*b*).
Nonionina sp.
Pulvinulina sp.
Textularia sp.
Truncatulina lobatula (?).

Though few species could be definitely determined, owing to the altered condition of the limestones, yet the general appearance of the material under the microscope was that of a typical Miliolina limestone, which suggests lower Tertiary age. These limestones, however, lie unconformably below the Arecibo formation, which is not later than Oligocene. From these species one may be forced to conclude that the upper part of the older series of the San Juan district is of Eocene age.

The lower members of the older series are wholly unfossiliferous. It is the writer's opinion, however, that the older series as expressed in this district is entirely post-Jurassic and probably post-Comanchic in age.

SUMMARY

The material composing the limestones, shales, and conglomerates, as well as the tuffs and ashes of the older series, is in great part derived from volcanic sources or through volcanic agencies.

The discordance in strike of some of the limestone beds, especially those near Aguas Buenas, indicates the presence of an unconformity in the older series, the limestones being older than the rest of the series. The conglomerate belt that extends across part of the district may also be taken as an indication of another break in the series.

The low content of inert refractory material in the rocks of the older series gives rise to an impervious soil that clings tenaciously to exceptionally steep grades.

Many of the formations show the effects of subsequent alteration. The tuffs are especially liable to the attack of modifying processes which have resulted in many cases in their being altered to extremely indurated and resistant rocks.

The formations of the older series are everywhere associated with igneous activity, expressed either as intrusions or by the invasion of liquid magma forming fragmental rocks with crystalline matrices.

The age of the older series is regarded as Cretaceous in its greater part. The uppermost portion is doubtless Eocene, and it is probable that the lower part is Comanchic in age.

IGNEOUS ROCKS

Modes of Occurrence

In all parts of the island the older series is characterized by an abundance of igneous rocks, showing a variety of forms and complex structural relations. After the deposition of the coastal plain strata, igneous activity apparently ceased, for in these formations no igneous rocks of any kind are found. It is possible, but improbable, that post-Oligocene intrusion has occurred in the older series of the interior, which has not affected the limestone strata of the coast. The modes of occurrence of the ignous bodies of the district are somewhat variable. Extrusive and intrusive rocks occur as lava flows, sills, dikes, and irregular intrusive masses, varying in complexity from a simple flow or single dike to an interrelated series of complex intrusives so intimately associated that accurate and complete differentiation is often wholly impossible.

LAVAS

The occurrence of lava flows in the San Juan district is comparatively rare. Several examples of such flows are to be found on the Comerio-Barranquitas road near K 35. At this point the lava flows occur associated with bedded and massive tuffs, dipping at steep angles. The lavas often show a vesicular habit which distinguishes them from the sill-like intrusives. In this locality and near the Bairoa River just north of Aguas Buenas strongly vesicular lavas are found. The vesicules are often filled with quartz, calcite, and zeolites, forming a fairly well developed amygdaloidal structure. The liquid lava occasionally seems either to have permeated the underlying ash and tuff beds, or to have been saturated with ashy and tuffaceous ejectments, forming a rock of tuffaceous appearance but of crystalline groundmass, which often proves very confusing to the geologist. The lavas found were almost invariably andesitic in composition.

SILLS

The most abundant of the simpler forms assumed by the igneous rocks are the intrusive sheets or sills. These are conformably intruded in the ashes and tuffs which are now tilted at steep angles or locally folded. The individual sills are usually thin, being often less than a foot thick and rarely more than a few feet in thickness, yet they are so numerous that they add materially to the total thickness of the formation in which they occur (Fig. 14). Except where modified by subsequent disturbance, the sills are almost perfect in form, and often show so indistinctly their intrusive nature that on weathering they are hardly distinguishable from the neighboring strata. Incorporation of tuffaceous material by the intruding magma frequently occurs, giving the sill a decidedly fragmental structure. Should such a sill occur in a series of tuffs composed of similar fragmental material, it might readily be entirely overlooked.

DIKES

Intrusives assuming the form of dikes are not uncommon in the district. Many of the existing dikes were probably overlooked or mistaken for more massive intrusives, where the outcrop showed none of the structural relations. It sometimes happens that a dike cutting some non-resistant formations such as the conglomerate at K 12.5 Comerio road, now stands out as a plainly visible topographic feature (Fig. 15). Such cases, however, are rare, for a dike intruding an igneous body of similar composition and resistance would only be revealed by a careful, detailed study of suitable exposures. Good exposures are to be had along the carreteras and principal stream beds; elsewhere the residual soil is so widespread

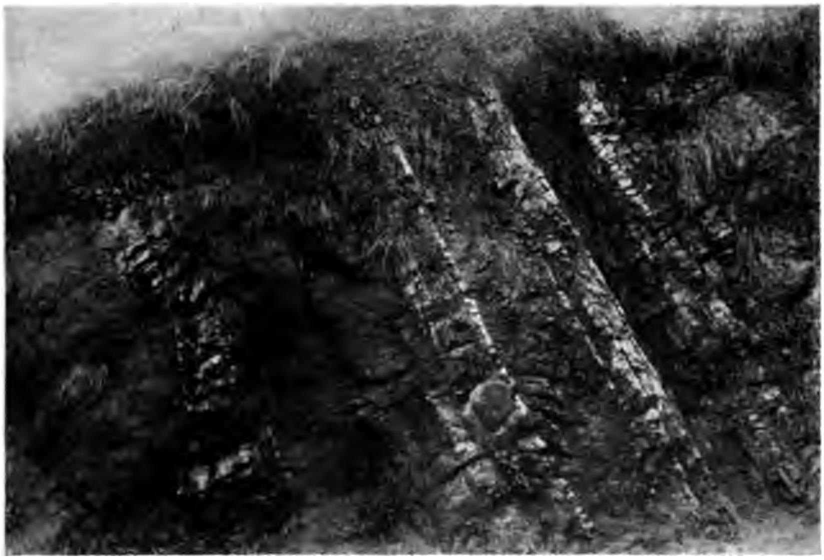


Fig. 14.—*Diorite porphyry sills intruded between layers of shales and ashes at K 20, Comerio Road*

The light-streaked and banded layers are shales and ashes; the massive portions, best seen on the left side of the print, are sills. Photographed by C. P. Berkey.

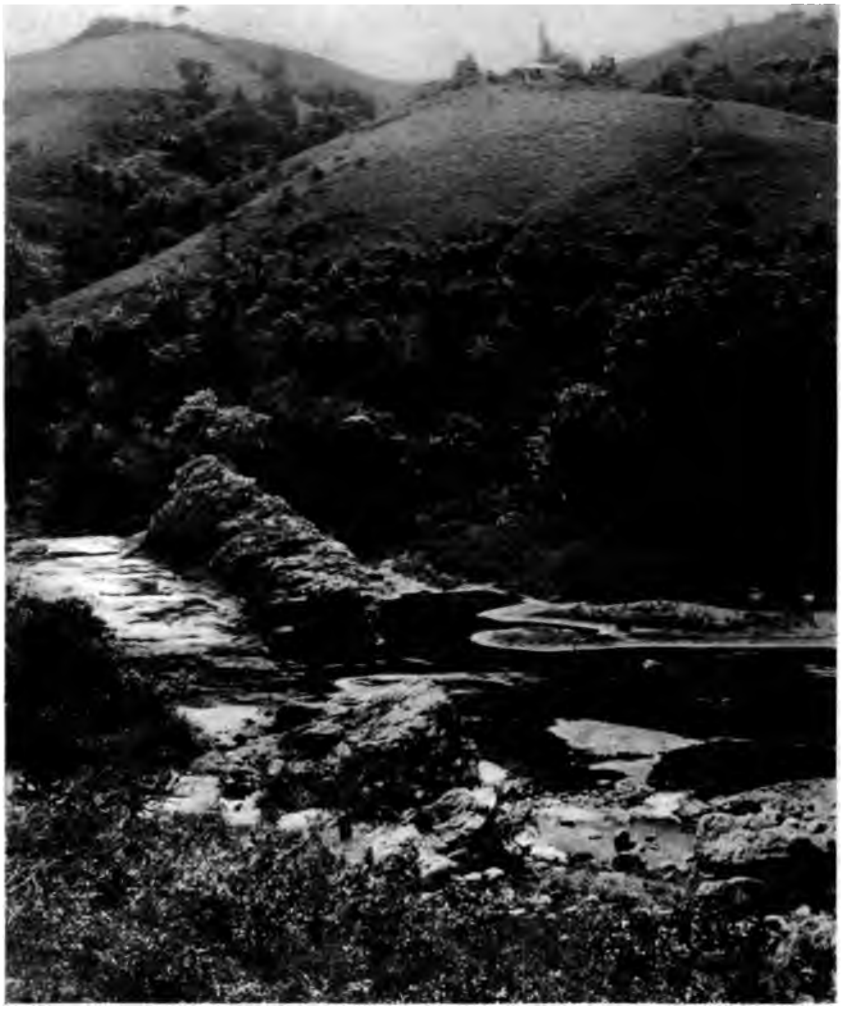


FIG. 15.— *Faulted trachyte dike crossing the La Plata River*

This dike is intruded in the conglomerate that crosses the Comerio Road at K 12-13.

that it is usually impossible to determine the underlying structure. The dikes vary in size from narrow stringers and apophyses from neighboring intrusives to massive structures many feet in width. The dike rocks are usually of felsitic texture. No relation between the coarseness of texture and the size of the dike could be discovered. The smallest dikes sometimes showed microgranitoid or even granitoid texture. The texture seemed rather to depend upon the conditions of intrusion than upon the size of the intrusives.

STOCKS AND BOSSES

The majority of the intrusive masses of the district should be classified as stocks and bosses, the term stock including all small batholithic intrusions, and boss being restricted to those stocks roughly circular in ground plan. It is often difficult to make this distinction unless the boundaries of the intrusive are accurately known. The stocks of the San Juan district are as a rule small. In the bed of the Bayamon River a perfectly formed stock not measuring over 20 feet in diameter was found. On the other hand, southwest of Morovis a large intrusive of granite covers an area of several square miles, and in other portions of the island intrusives 10–12 miles in diameter have been found. Large intrusives, however, are rare in the San Juan district. Only two, covering an area of over a square mile, were located. The majority were less than 100–200 yards in diameter. Fragmental inclusions are characteristic of all the stocks of the district. In the larger ones these inclusions may be of large dimensions. In the granite southwest of Morovis inclusions of the adjacent tuffs measuring many feet in diameter were found. It frequently happens that the invading magma incorporates quantities of tuffaceous material. Such a rock, after consolidation, will so resemble a massive tuff that it will often be confused with one. Several specimens collected from supposedly massive tuffs proved after microscopic examination to have a crystalline structure. The variation from the massive crystalline to the tuffaceous phase of an intrusive may be so gradual that no line of demarcation can be made, or so sudden that it appears as if the boundary of the intrusive has been passed and that the tuffaceous phase of the intrusive is a separate formation of massive tuff.

TEXTURE

Rocks of felsitic texture proved the most abundant in the district. Almost all of these showed porphyritic habit, often not discernible in the hand specimen but evident from microscopic examination. An evidence of the almost universal tendency toward the porphyritic texture in the felsitic rocks is that many of them show three generations of crystals more or less perfectly developed. The larger phenocrysts occur in a matrix of smaller phenocrysts and a felsitic groundmass (Fig. 23). Though the rocks are predominantly porphyries of felsitic texture, yet quite a variety of textures and structures are encountered in a study of much material. No true glasses were found, but a rock of vitrophyric texture, in which the glassy groundmass made up most of its bulk, was seen (Fig. 16).

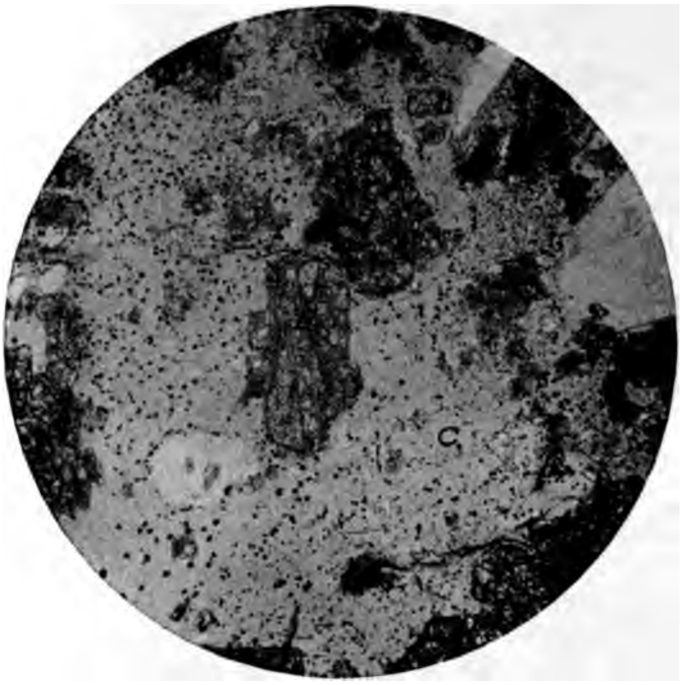


FIG. 16.—*Photomicrograph of vitrophyr occurring north of Cidra*

E. Feldspar phenocrysts altered to epidote. C. Chloritized glassy groundmass.

Another specimen shows a peculiar radial, felt-like structure much resembling that of a natural slag (Fig. 22). Microgranitoid texture is common among the larger intrusives. Rocks of granitoid texture are abundant and widespread, but none of the coarser granitoid rocks showed pronounced porphyritic texture.

COMPOSITION

The igneous rocks of the district are fairly uniform in composition. The predominant type is an andesitic, or the coarser-grained dioritic equivalent. The widespread occurrence of andesitic types is noticeable in the fragmental material constituting the ashes and tuff as well as in the igneous rocks *in situ*. Many of the tuffs are wholly made up of andesitic material. However, when one is afforded the opportunity of examining a variety of material, such as is to be seen in the boulder beds of any of the streams that drain a large area of the older series, one soon realizes that considerable variety in composition is represented. In examining petrographically the material brought from the district, the writer found almost every variety of the igneous rocks from acid to medium composition. Basic rocks, however, were uncommon; basalts and olivine basalts being rare, and typical gabbros or more basic rocks almost unknown.

As almost every square foot of the older series is intruded or modified by igneous rocks, it would obviously be impossible to attempt to describe each individual intrusive or to locate them geographically. Accordingly, they have been grouped on a basis of composition, and the more important members of each group will be briefly discussed. The gradations from one group into the next usually proceeds so uniformly and gradually that the introduction of several intermediate groups is unnecessary. A comprehensive classification of the igneous rocks of the district should include all of the following varieties:

Vitrophyrs
Rhyolites
Granites
Quartz latites and Rhyo-andesites
Quartz monzonites
Granodiorites
Dacites
Quartz diorites

Trachytes
Syenites
Latites or Trachy-andesites
Monzonites
Andesites
Diorites
Basalts
Olivine basalts

VITROPHYRS

These rocks are of rare occurrence in the San Juan district. On the trail between Aguas Buenas and Cidra, about a mile north of Cidra, there is a prominent outcrop of a rock which proved on microscopic examination to be a vesicular vitrophyr. Phenocrysts have for the most part been altered or completely weathered out, and the cavities since filled with epidote, chlorite, and quartz. The glassy groundmass is still fairly fresh, but there seems to be some indications of incipient devitrification. The rock shows a slightly fragmental structure and occasionally the outlines of former large crystals are to be seen, but these are believed to have been inclusions rather than original constituents of the rock (Fig. 16).

RHYOLITES

Rocks of rhyolitic composition are also quite rare. The best example was seen northeast of La Torrecilla in barrio Barrancas. This is a porphyritic rhyolite with phenocrysts of quartz, orthoclase, and mica in a fine-grained acidic groundmass. The whole rock has subsequently been highly sericitized (Fig. 16*a*). In the Bayamon Valley just east of Helechal Peak a number of acidic intrusives were found, among which were several rhyolite porphyries.

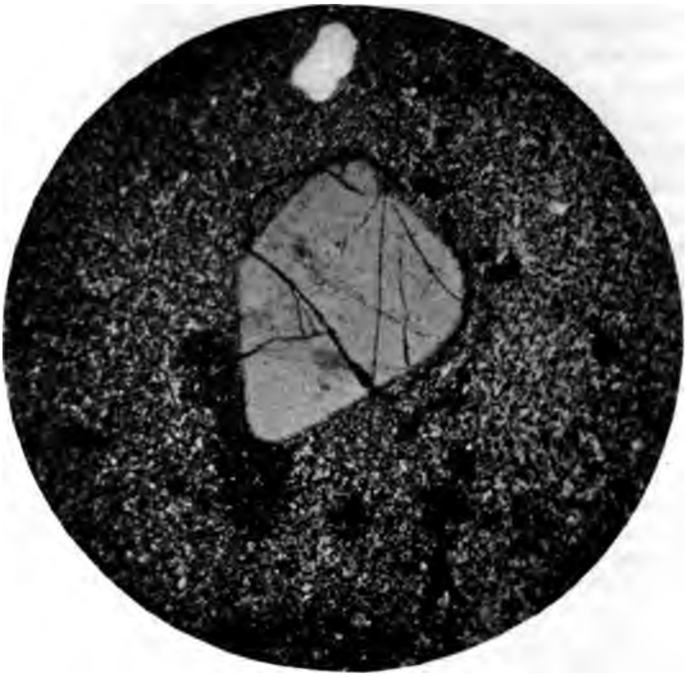


FIG. 16*a*.—*Rhyolite porphyry*

Large phenocryst of quartz in center, crossed nicols.

GRANITES

Granitic intrusives are widespread and fairly abundant. All of those studied microscopically proved to be rich in soda feldspar, or that variety known as soda granites. The large intrusive mass which covers an area of several square miles southwest of Morovis is of this composition. The rock is light-colored, with scattered patches of the darker ferromagnesian minerals, and coarsely crystalline in texture. It is composed chiefly of quartz, plagioclase, orthoclase, and hornblende, with scattered titanite.

magnetite, and apatite crystals. This intrusive is especially interesting in that it shows a well-developed poikilitic structure. The plagioclase, hornblende, and titanite crystals occur in the orthoclase, which shows no crystal outline. The orthoclase apparently crystallized last with the quartz, both now occurring as interstitial material (Fig. 17). Minute veinlets of secondary hornblende and actinolite occasionally traverse the rock for short distances. Minor copper impregnations were seen at several points, but these occurrences were of no economic importance. A smaller intrusive of similar composition was found on the mountain slope just south of Naranjito (Fig. 18).

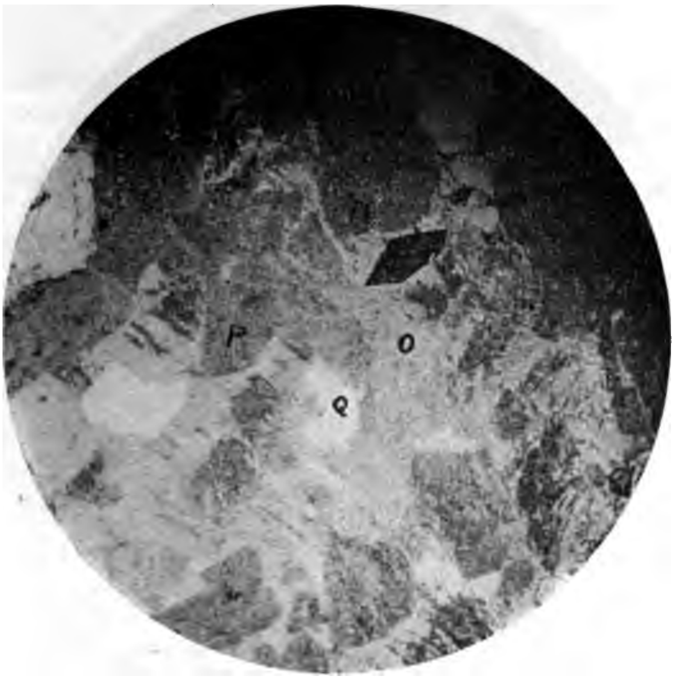


FIG. 17.—*Soda granite, showing poikilitic structure*

Phenocrysts of plagioclase, hornblende and titanite in orthoclase and quartz. P. Plagioclase. H. Hornblende. T. Titanite. O. Orthoclase. Q. Quartz.

QUARTZ LATITES AND RHYO-ANDESITES

In the felsitic rocks where the individual crystals that constitute the groundmass are too small to be accurately determined, the finer distinction in variety cannot be made. Accordingly, the quartz latite and rhyo-andesites, the felsitic equivalents of the quartz monzonite and granodiorites, respectively, are grouped together. Felsitic rocks of this composition are occasionally found. They consist chiefly of quartz and lime-soda feldspar with notable amounts of potash feldspar and subordinate ferromagnesian minerals. Such rocks are also known as dellenites.[8] A typical example of this group is to be found north of Aguas Buenas. The specimens collected consisted of phenocrysts of quartz, feldspar, predominantly the lime-soda variety, and mica, in a fine-grained groundmass.

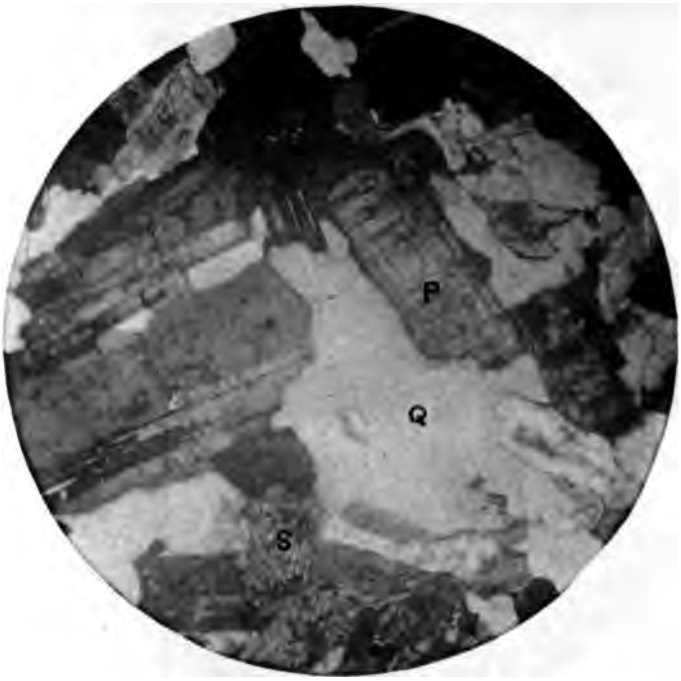


Fig. 18.—*Soda granite occurring south of Naranjito*

P. Plagioclase (oligoclase). Q. Quartz. M. Magnetite. S. Sericitized feldspar.

This rock occurs associated with other acidic rocks of almost the same composition, and is doubtless merely a differentiated phase of some larger intrusive.

QUARTZ MONZONITES

These are granitoid rocks consisting chiefly of quartz, medium plagioclase, with considerable orthoclase. With these may occur biotite, hornblende, or pyroxene. They are the closest associates of the granites and are often classed as such. They differ only slightly from the soda-granites already described, yet they serve to express a somewhat more alkaline step in the continuous series of intergrading varieties that is characteristic of the igneous rocks of the district. A small intrusive of this variety was found in the bed at the Bayamon River in barrio Sonadora. It is a massive granitoid rock of bluish color, made up of quartz plagioclase, orthoclase, and hornblende. The rock has subsequently been somewhat sericitized and carbonated.

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[8] Brögger, 1895.

GRANODIORITES

The granodiorites are granitoid rocks of nearly the same composition as the quartz monzonites. They contain less potash feldspar than the latter and more of the lime-soda varieties, that is, they are intermediate in composition between the quartz monzonites and quartz diorites. Southwest of Naranjito, in barrio Cedro Abajo, a fairly large intrusive of this composition was encountered. From a casual examination it would be classed as a granite, but under the microscope it is seen to consist chiefly of quartz and plagioclase (oligoclase) with subordinate orthoclase and hornblende and scattered crystals of magnetite, titanite, and apatite. This intrusive shows striking mineralization, which apparently took place in two stages; first, the introduction of additional magnetite, then sulphide solutions entered and deposited pyrite around the magnetite grains.

DACITES

Those rocks of andesitic composition which contain appreciable amounts of quartz are here grouped as dacites or quartz andesites. This variety is rare and only one typical example was found among the rocks studied, which occurred on the military road near La Muda. It is a porphyritic dacite, consisting essentially of phenocrysts of plagioclase (oligoclase), biotite, and quartz. All the constituents have been somewhat altered, especially the biotite, which has been replaced by chlorite, carbonates, and bleached mica. The intrusion has taken place through a series of coarse tuffs, and some of this material has been incorporated into the intrusive itself, giving it a fragmental structure.

QUARTZ DIORITES

The quartz diorites are more abundant than their felsitic equivalents, the dacites. Two miles southwest of Morovis an intrusion of this variety occurs in the large intrusion of soda-granite already described. Another example was found at K 5 on the Comerio road. This is, no doubt, merely a more acid phase of the adjacent diorite intrusives (Fig. 19).

TRACHYTES

Trachytes consisting chiefly of orthoclase and biotite or hornblende or pyroxene are comparatively rare. The majority of the trachytic rocks show more of the alkali-feldspars. These in turn grade into the latites and andesites. Typical trachytes, however, were occasionally found. Near K 17, on the Comerio road, one was found, another about a kilometer southwest of Helechal Peak, and on the trail half mile north of Cidra a trachyte was noted that showed fairly well-developed trachytic structure (Fig. 20).

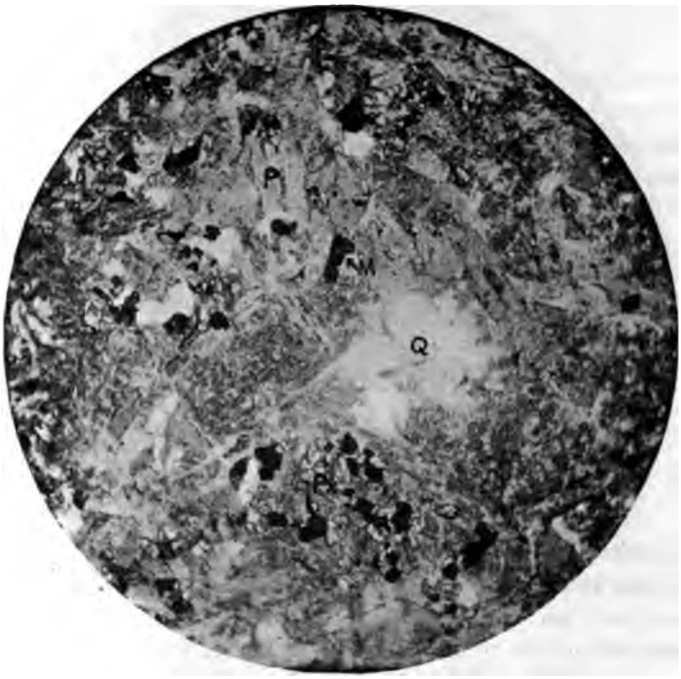

FIG. 19.—*Quartz diorite*

Q. Quartz. P. Plagioclase. Px. Pyroxene. M. Magnetite.

SYENITES

The granitoid equivalents of the trachytes are very uncommon. Only one true syenite was found in the material examined under the microscope. This was an intrusion occurring at K 20.5 (Comerio road) composed almost entirely of orthoclase with minor amounts of plagioclase, hornblende, and magnetite.

LATITES (TRACHY-ANDESITES)

These are felsitic rocks composed of potash feldspar and lime-soda feldspar in approximately equal amounts, with subordinate ferromagnesian minerals. They are very abundant throughout the district, forming the second most important type that is found, and being almost as widely distributed as the related andesites. They are usually porphyritic in texture, occurring as small intrusives and flows, sometimes showing amygdaloidal habit. Diopside is the chief ferromagnesian mineral. Occasionally hornblende forms an important constituent, and rarely biotite. Some secondary alteration has taken place in all the material examined. Sometimes alteration has advanced so far that the original constituents cannot be absolutely determined. The commoner alteration products are

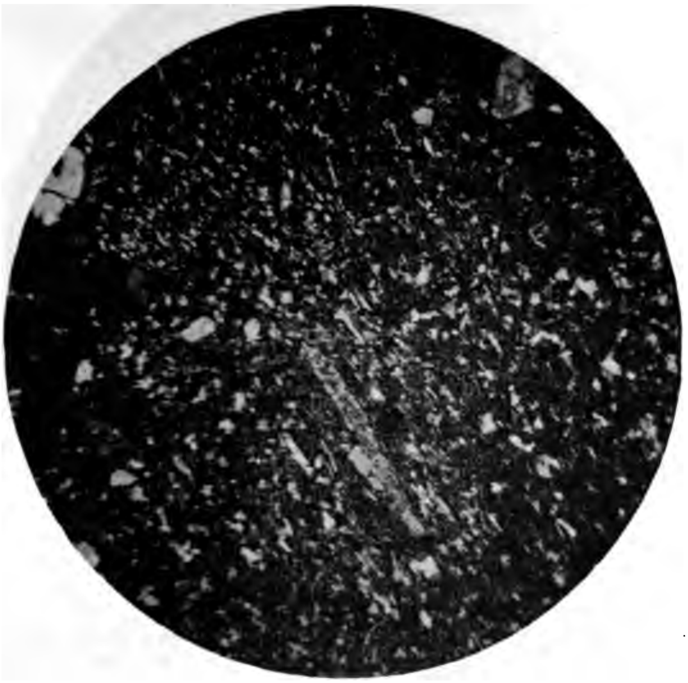

FIG. 20.—*Trachyte, showing poorly developed trachytic structure, crossed nicols*

sericite, chlorite, epidote, and calcite. Kaolin, iron oxides, and leucoxene also frequently occur in appreciable quantities. Since the latites are not distinguishable from the andesites in the field, no attempt will be made to list their occurrence. Many of them were there simply designated as andesites, and no specimens were collected for microscopic study (Fig. 21).

MONZONITES

The monzonites, or granitoid equivalents of the latites, are much less widely distributed. Many of the intrusives simply termed diorite in the field could probably have been referred to this group had they been examined microscopically. Two intrusives of this variety are to be found on the Comerio-Barranquitas road at K 35.5 and K 39.7. They are microgranitoid rocks, consisting of lath-shaped orthoclase and plagioclase crystals arranged in a coarse, felt-like aggregate with subordinate amounts of pyroxene and hornblende.

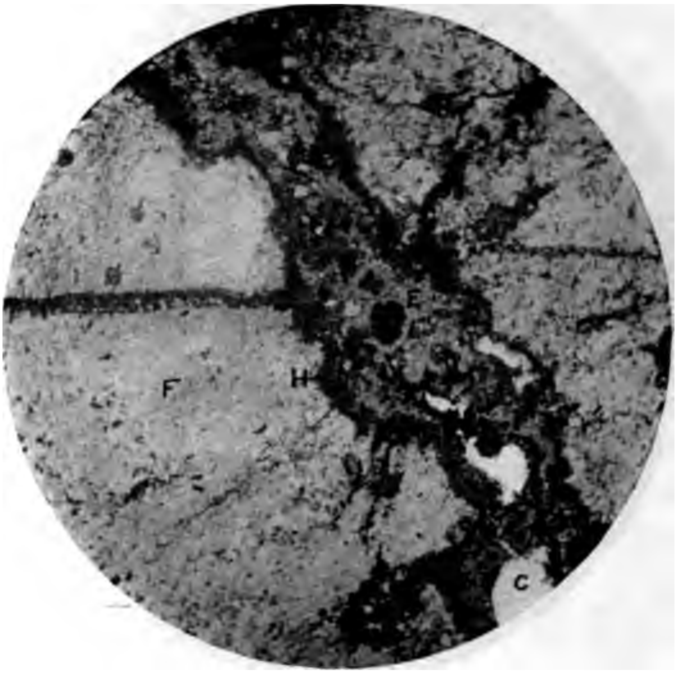

FIG. 21.—*Latite, showing veins filled with epidote and iron oxides*

F. Feldspars. E. Epidote. H. Hematite. C. Cavity.

ANDESITES

The andesites are the most abundant as well as the most widespread of the igneous rocks. They are usually of porphyritic texture and assume all the structural forms that are represented in the district. The essential constituents are plagioclase of medium composition (oligoclase and andesine), and lesser amounts of orthoclase, pyroxene (usually diopside), and hornblende. Certain varieties of the andesite porphyries in which the phenocrysts were chiefly feldspar showed a spotted appearance due to the white feldspar phenocrysts in a dark groundmass. Other varieties in which the phenocrysts were composed chiefly of the ferromagnesian minerals had a darker and more basic appearance. Diopside is much the most abundant of the ferromagnesian minerals; hornblende occurs infrequently, and biotite quite rarely. The present mineral constituents of many of the andesites are largely the result of secondary alteration. Some of them contain such large quantities of secondary carbonates that they effervesce slightly in cold dilute acid. Sericite, chlorite, kaolin,

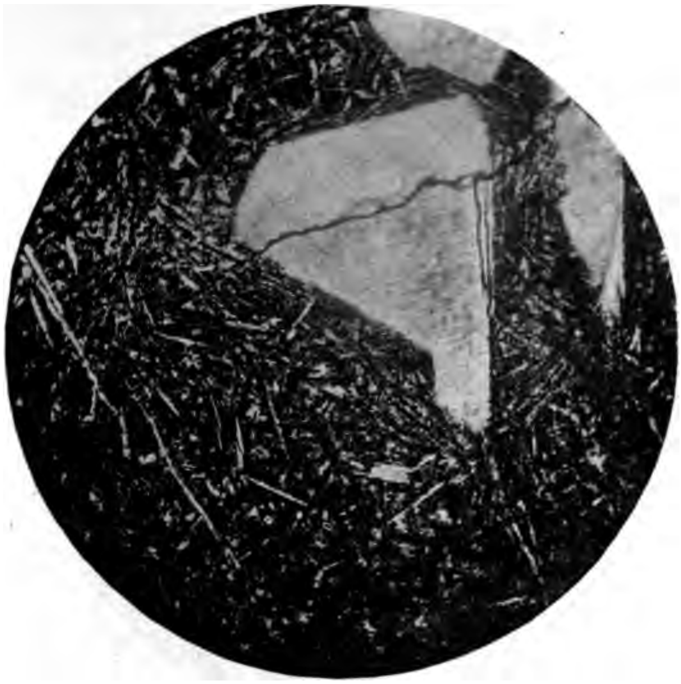

FIG. 22.—*An andesite porphyry with large phenocrysts of plagioclase surrounded by a groundmass, showing the structure of a natural slag*

epidote, iron oxides, and quartz commonly occur and occasionally constitute a large percentage of the entire mass of the rock. A few of the more striking members of this group are herewith briefly described. At K 17 on the Comerio road a porphyritic hornblende andesite was found. Secondary alteration had greatly changed the original constituents of the rock. The original outlines of the hornblende phenocrysts could be clearly seen, though the hornblende itself had been changed into sericite, calcite, and chlorite. Another hornblende andesite was found at K 41 on the Military road, south of Caguas. On the Barros-Corozal trail an epidotized andesite porphyry was found. The rock consisted chiefly of epidote and plagioclase. Three distinct generations of crystals were shown. Another epidotized andesite is located just north of Aguas Buenas near the river Bairoa. This is an amygdaloidal andesite with epidote filling the cavities. On the Comerio road at K 5 an andesite porphyry with a remarkable radiating, felt-like groundmass was discovered. Its structure resembles very much that of a natural slag (Fig. 22).

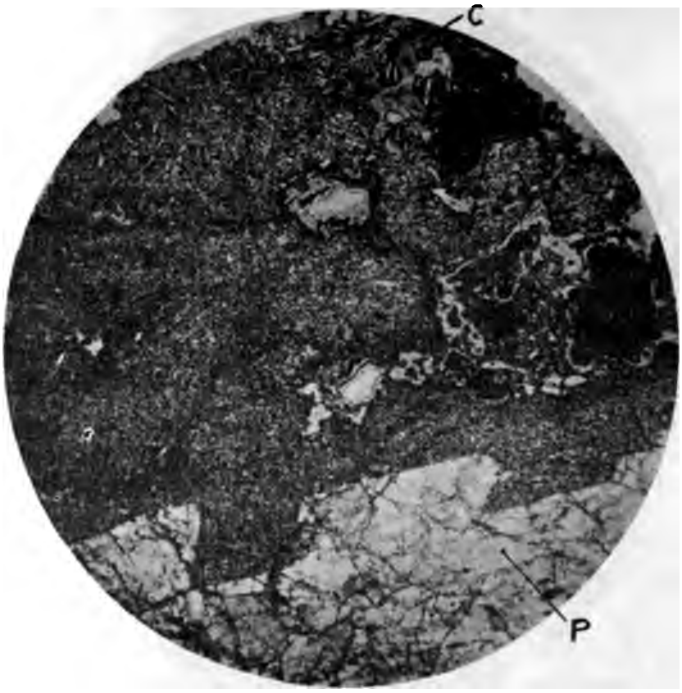

FIG. 23. *Andesite porphyry impregnated with chrysocolla. Barrio Pasto*

P. Plagioclase. C. Chrysocolla.

One of the two largest intrusives in the district is an andesite porphyry. It occurs just south of the Orocovis River on the Morovis-Barros road, extending out of the district on the west. Large phenocrysts of light-colored feldspars in the dark groundmass gives the rock a spotted appearance. It is in this rock that the copper prospects of barrio Pasto occur. From microscopic examination it is seen that this rock also shows three generations of crystal growth. Large phenocrysts occur in a porphyritic matrix of smaller, lathe-shaped feldspars and a felsitic groundmass (Fig. 23).

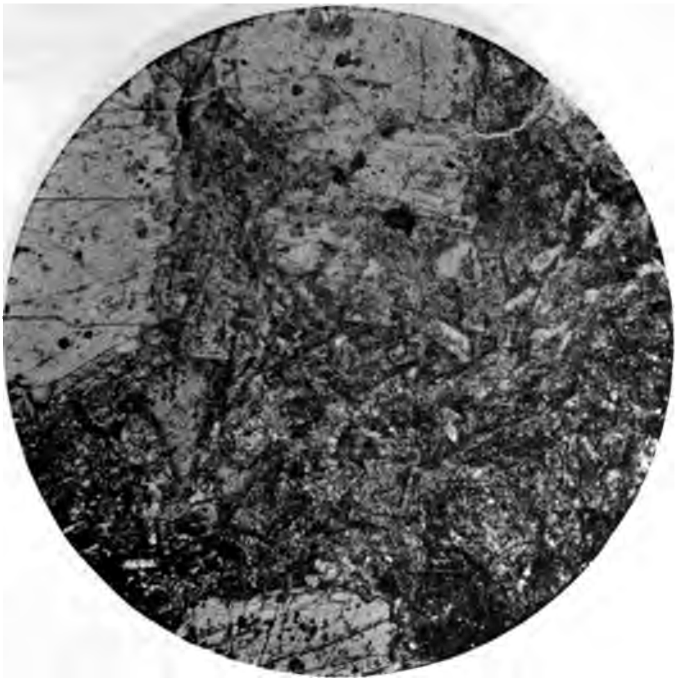

FIG. 24.—*Diorite porphyry with pyroxene phenocrysts in a groundmass of lath-shaped feldspars (plagioclase)*

DIORITES

Intrusives of dioritic composition are of frequent occurrence, though not so widespread as the andesites. They are as a rule dense, massive, dark bluish rocks often showing large phenocrysts of pyroxene. They consist chiefly of plagioclase feldspar and pyroxene, with subordinate amounts of orthoclase and hornblende. Diopside is much more abundant than augite. Many of the diorites show fragmental structure. Some of them have incorporated so much fragmental material that they may be mistaken for tuffs. The diorites are uniform in composition and general appearance, and when not modified by inclusions are readily recognized in the field (Fig. 24).

BASALTS

Many of the andesitic rocks might be mistaken for basalts by the casual observer, but typical basalts are decidedly rare. Basic varieties of andesites which have been called basalts are more common, but all of these rocks, though basaltic in appearance, show only the intermediate varieties of the plagioclase feldspars. At K 12, on the Comerio road, an amygdaloidal porphyritic rock of basaltic appearance intrudes the tuffs. It is composed of lath-shaped phenocrysts of plagioclase in a dark, basic groundmass of ferromagnesian minerals. The vesicular cavities have been filled with quartz and zeolite. While this rock has a typical basaltic appearance, the plagioclase shows low extinction angles (less than 10°).

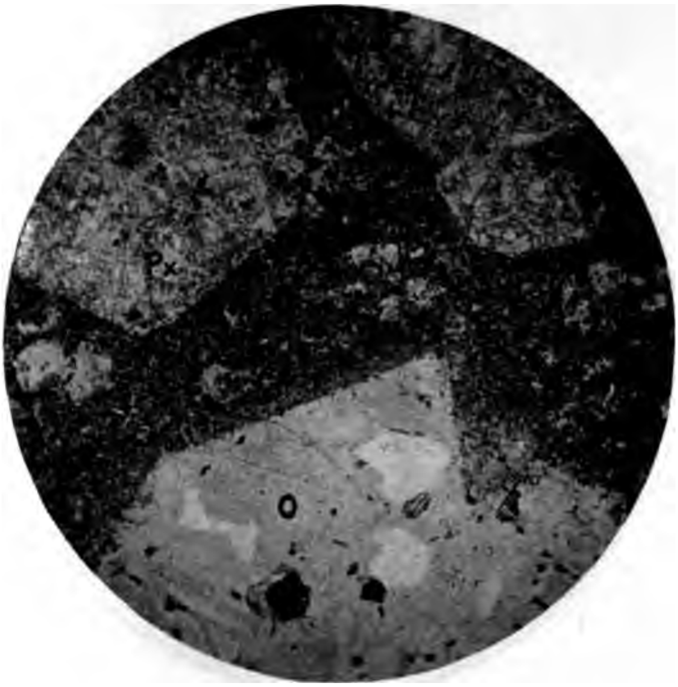

FIG. 25.—*Olivine basalt*
O. Altered olivine. Px. Pyroxene.

which indicate that only the acidic varieties are present. Hence the rock should correctly be classed as a basic andesite.

OLIVINE BASALTS

Only one olivine basalt was found in the material collected for microscopic study. This was an intrusive body about two miles south of Corozal. It is of porphyritic texture, consisting of phenocrysts of olivine, and, to much less extent, plagioclase, in a groundmass composed chiefly of plagioclase and magnetite. The olivine was largely altered to serpentine and chlorite. The feldspars have likewise been so chloritized that their exact composition was indeterminable (Fig. 25).

No rocks of gabbroic or more basic composition were found in the district.

SUMMARY

No definite conclusions can yet be drawn as to the exact range in composition of the igneous rocks of the district or their relative abundance, for by no means all of the igneous bodies have yet been located. In the present survey all of the larger instrusives were located, and many of the smaller ones, where well exposed in stream beds and along the carreteras. There remains undiscovered a large number of minor igneous masses either covered by the residual soil or located between the traverses that were made. Sufficient material has been collected and studied, however, to give an accurate idea of the general range in composition and form of the igneous bodies. In the preceding pages minor differences and variations in composition have been unduly emphasized in order to give a correct idea of the relative range in composition, and the continuous gradation that exists between the more acid and basic varieties. The usage of many of the varietal terms that have been introduced here would be inadvisable for ordinary field work and general description.

The petrographic study of the igneous rocks of the San Juan district can be summarized as follows:

(1) The structural forms assumed by the igneous rocks of the district are of various sizes and shapes. The sills and stocks occur most commonly, while lava flows are rare.

(2) The igneous rocks are predominantly felsitic in texture. No relation of texture to size of the intrusive could be observed.

(3) The rocks of felsitic texture are almost invariably porphyritic. The porphyritic habit is sometimes poorly developed, but in some cases

cates another break in the older series. To the southwest of this conglomerate the formations strike N. W.–S. E. with hardly an exception. Northeast of it outcrops are rarer. The shale beds for the most part appear to strike N. W.–S. E., but the sandstone at K 8 gives an exceptional strike of N. 65° E. Northeast of the conglomeratic Muda tuffs no strikes were obtainable from the few scattered outcrops. Berkey, however, noted that the shales on the Military road south of Rio Piedras strike E.–W., and the tuffs farther south strike N. 20° E.

The variations in strike over the northeastern portion of the district are at first very confusing, but when one considers that the material forming the sediments is of volcanic origin and was not derived from a single source, but probably from many vents, it seems surprising that any uniformity in strike would exist over an extended area. The volcanic material ejected from a number of vents would be concentrically deposited around each, forming a succession of local formations interfingering with the deposits from neighboring vents. Intense igneous activity has accompanied the deposition of all this tuffaceous material, and finally the whole complex thus formed was uplifted and folded by subsequent dynamic movements. The end-product of such a series of events would be a volcanic ash heap of great complexity, in which extended series of conformable beds would be the exception rather than the rule. Considering Porto Rico as a portion of such a mass, one can better interpret the many complex and erratic structures that are to be found as well as the local character of many of the formations which are so confusing to one who attempts a solution of the areal geology of a portion of the island.

FAULTING

Indirect evidences of faulting are abundant, but in no case was the displacement itself visible nor the amount of movement determinable. Abrupt changes along the strike of certain formations indicate faulting on a large scale, but outcrops were too scattered to determine positively their presence. Evidence of faulting on a small scale is much more abundant. Along the Comerio road occasional shear and crush zones are visible, which apparently involve faults of some magnitude. The best examples occur at K 17 and K 21.5. In both cases, however, the complexity of the structure involved was so great that no accurate estimate of the amount of movement could be made.

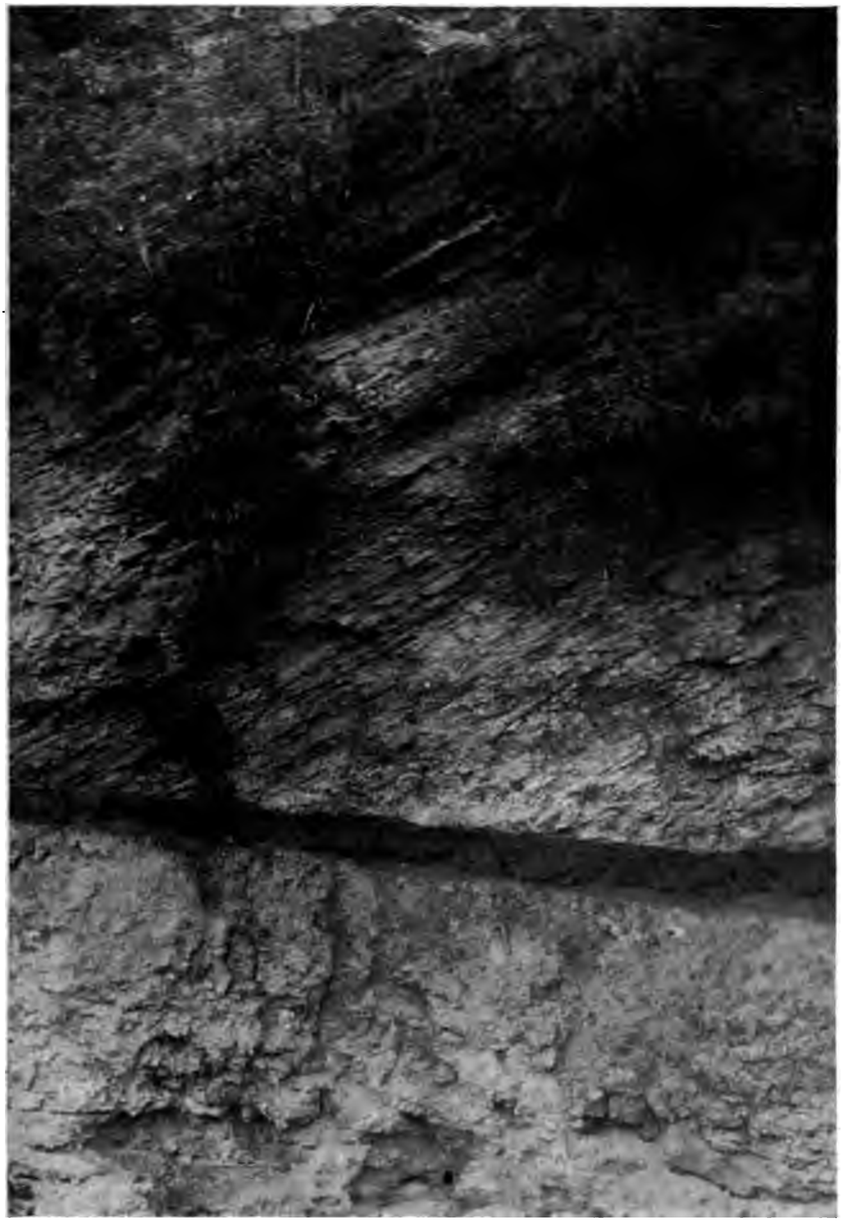

FIG. 26.—*Cross-bedded structure in the San Juan formation at Arecibo*

The horizontal marks crossing the inclined layers in the upper part of the picture are of supposedly secondary origin. Photographed by C. P. Berkey.

FOLDING

All of the sedimentary formations of the district show some folding or tilting. The limestones of the coastal plain have been only slightly tilted. Their maximum inclination is not over 10°, and no indications of folding or warping within the formations themselves could be discovered. The beds of the older series are characteristically highly tilted, and in many places well-developed folds are to be seen. The folding is on a small scale and is confined to certain less competent shales and ash beds. The fact that the sediments generally dip towards the sea on both sides of the island would suggest the possibility of a large anticline with the axis along the crest of the island. Minor folds are not uncommon in the shale series that forms the divide in the southern part of the district. Moreover, this shale series is anticlinal in its larger structure, with its crest just north of Barranquitas—a fact which gives additional weight to the theory of anticlinal structure for the older series as a whole.

METAMORPHISM

No evidence of regional metamorphism was found in the rocks of the older series. Evidence of contact metamorphism is also surprisingly scarce. The amphibolite already described is the only rock found that might safely be regarded as due to contact effects.

MINOR STRUCTURES

CROSS-BEDDING

The San Juan sandstone shows well-developed cross-bedding of the eolian type. Berkey (1915, p. 43) has described with some detail the double character of the cross-bedding where it is best exposed near Arecibo (Fig. 26).

SOLIFLUCTION

The crumpling, due to the slumping of certain formations, either from external pressure or from the force of its own gravity, gives rise to what has been termed solifluction. This type of structure was noted in several of the thinly bedded ash formations, but it was best developed in the Juan Ascencio chert bed, which has been previously described (Fig. 11).

STRATIGRAPHICAL SUMMARY

The geological history of the island of Porto Rico has already been comprehensively summarized by Berkey (1915, p. 58). Little can be added to this from the data collected by the writer, except certain changes in the age relations of the formations. The geological history of the San Juan district or that of the whole island, for the former involves practically every step of the latter, still remains in great part uncertain. An accurate and detailed statement of it can only be hoped for as an end-product of the series of investigations that are now in progress. Each investigator, however, can contribute his share toward the final result. The writer, therefore, re-summarizes the historical statement of Berkey, making those modifications which he thinks are justified by subsequent investigation.

As stated above, the formations that compose the so-called "older series" were early recognized to be geologically young. While some of the shales and limestones have the appearance of being older than they really are, yet none of them is at all similar to the so-called "ancient rocks" of other regions. The age of the lowermost member of the older series is still undetermined except in the most general sort of way. The discovery of a Comanchic coral by Mr. Hodge in the shales south of Cidra indicates that these shales, which apparently form the base of the older series, are no older than the Comanchic age. Flanking these shales both to the north and south are the succeeding members of the older series, which are, as a whole, younger. Such a succession of the members of the older series would suggest a large anticline extending across the island along the belt surveyed by the writer and Mr. Hodge. Other portions of the island, however, do not support this theory, for a section from Arecibo to Ponce shows no indication of the anticline. The writer merely suggests it for the San Juan district and the district to the south, because the shales which form the crest of the island at Barranquitas are anticlinal in structure and are flanked on either side by younger formations. Whether the Barranquitas shales are regarded as the oldest formation of the older series or not, there still remains little reason for supposing that the base of the older series is older than Comanchic. Indeed, the whole of the older series might well have accumulated in a single geologic age, for all of its members give indications that their accumulation was, for the most part, a rapid process.

The deposition of the various members of the older series was accompanied by igneous activity on a very large scale. Great masses of volcanic ejectments were thrown forth to accumulate in fan-like deposits both above and below sea level. This was accompanied by periods of submergence during which the shaly and calcareous beds were deposited, and periods of emergence in which the recently formed sediments were uplifted and sometimes shattered by later volcanic outbursts. During the accumulation of the older series there seems to have been no great change in the nature of processes that took place. No change of sufficient magnitude occurred by which the series might be readily subdivided. It is true that changes in physical condition, such as would cause a shale or ash to accumulate instead of a tuff, frequently occurred—so frequently that these minor changes cannot be used as a basis for consistent subdivision. With the exception of the large conglomerate that crosses the greater part of the district from southeast to northwest, there is no formation which can be used as a definite division line. Other divisions are not even continuous across the San Juan district, and might never be recognized in the adjoining districts.

In early Eocene time this period of volcanic activity finally came to an end. Naturally, from the time of the first volcanic outbursts portions of the island had been dry land. Toward the end of the period of volcanic activity the lower portion of the older series must have been above sea level. This land-mass afforded the material for the late Cretaceous and early Eocene foraminiferal shales and limestones. It is probable, therefore, that much of the island had been reduced to a submature or mature stage of topographic development before the final cessation of volcanic activity. As such activity completely ceased, erosion continued and the entire island was reduced to a peneplane or to an old stage of topographic development. The development and extent of this peneplane have already been discussed. Until the whole island is examined with this point in mind it will be impossible to say to what extent it was developed. The period in which it culminated, however, was geologically short. Eocene formations are found beveled by the peneplane, and Oligocene strata lie above it.

As the erosion of the older series proceeded, sediments were deposited unconformably around the margins of the island as it existed then. In shallow water, and doubtless in the estuaries and bays of the coast of that time, were first deposited a series of shales. This phase of deposit was not well expressed in the San Juan district, but to the west it is represented by the San Sebastian and Lares shales. This earlier stage in the deposition of the younger series probably occurred before the interior had been reduced to an old stage of development. As erosion continued, clearer water conditions prevailed and the lower shaly beds of the Arecibo limestone were deposited. Later, after clear water conditions had become stable, the upper pure limestone and reef limestones were finally deposited.

At the beginning of Miocene time there was a marked emergence, and the early Tertiary limestones and shales were elevated to essentially their present position. This emergence was accompanied by warping, so that now these strata are inclined at an angle of about 6°. From that time until the present, these formations have been subjected to erosion, and in consequence the comparatively easily destroyed limestones and shales have been maturely dissected or almost completely removed.

Since this emergence there have been frequent minor movements, extending down to recent time—movements that have been rcorded in the marginal terraces by the occurrence of marine shells at considerable distances up the larger river valleys, and by the partial submergence and induration of the San Juan dune sand. The latest movement has apparently been one of slight emergence.

Berkey (1915, p. 60) summarizes the more important steps in the geologic history as follows:

> 1) A long geologic period of volcanic activity, accompanied by marginal attempts at assorting of fragmental and detrital material and organic accumulation disturbed from time to time by renewed or extended igneous activity.
>
> 2) A dying out of volcanic energy, greater stability of the mass with respect to elevation and subsidence, and erosional attack continued long enough to result in extended planation and partial base-leveling with final extensive submergence.
>
> 3) The development of an unconformable overlying series of shales, reef limestones and related deposits chiefly of organic origin, brought to an end by final re-emergence.
>
> 4) The development of present surface features under stream erosion and marine marginal attack, with modifications arising from oscillation of level.

The geologic column of the formations of the San Juan district is the same as that formulated by Berkey (1915, p. 61) for the entire island, with certain minor modifications:

Recent alluvial deposits
    Submergence with marginal (playa) deposits
Younger series
    San Juan dune sand (Pleistocene?)
        Submergence with terrace cutting
        Post Arecibo emergence and erosion (Miocene)
    Arecibo formation (upper Oligocene)
    Lares shales, etc. (Lower Oligocene or upper Eocene) not expressed in San Juan district
    Marked unconformity

Older series
  Corozal and Muda limestones (Eocene)
  Foraminiferal shales and limestones (Unibon shale, shale at K 8, Comerio road) (Upper Cretaceous)
  Barranquitas shales and shaly limestones. Probably the base of older series (Comanchic ?)

MINERAL OCCURRENCES

Throughout Porto Rico there is evidence of widespread but apparently feeble mineralization, which has given rise to a variety of mineral deposits of small extent and uncertain importance. Mineralization in the San Juan district has produced even less results than in other portions of the island. Prospects occur in considerable variety, but no extensive deposit was found in this district. Up to the present time none of the mining ventures that have been promoted in the district has proved a success. This, however, has not been due wholly to the low quality and limited quantity of the ores encountered, but is due partly to the difficulties in transportation and the mining methods employed. Without the exercise of caution and economy in the development of small ore bodies such as are found in the district, success cannot be expected. Much money has already been wasted by attempting more elaborate methods than are warranted by the extent and quality of the ore occurrences.

The prospector is soon impressed by the extent of the mineralization in the igneous rocks of the older series. Numerous examples of mineralized igneous rocks have already been cited. An abundance of magnetite and pyrite are to be found in almost all the igneous rocks of the district, yet the resultant ore deposits are surprisingly small and unimportant. Native gold from quartzose zones and placers is the only metal that thus far has been produced in paying quantities. Indications of copper are abundant, but in only one locality does it occur in sufficient quantities to attract development. Non-metallic deposits of value are entirely wanting, except, perhaps, limestones for road metal or similar uses.

GOLD

PLACERS

The principal gold placers of the island are located in the vicinity of Corozal. From the streams in this vicinity gold has been washed by the natives since the days of early Spanish occupancy. Tales of the great abundance of gold and the size of the nuggets found during those early days are widespread and form a favorable subject of conversation among the older native panners. No statistics are available, however, either to disprove or verify these statements. It cannot be denied that a large amount of gold has been panned out of the streams of this vicinity in past time. At present the work is slow and tedious and pays poorly even in the most favorable localities. The native panner stands up to his neck in a pool, which he has dug in the stream bed, and assiduously scrapes up the fine sand in a cocoanut shell, separating the larger pebbles by hand. If the pool is deep he dives to the bottom for the sand. If ten hours of this work nets him eighty cents he is fortunate, for the average daily washings do not exceed fifty cents. Indeed, the peon prefers steady farm labor at forty to fifty cents per day to the precarious living he can derive from the stream beds. During recent years about 100 ounces of gold are annually washed from the streams of the island, the larger part coming from the Corozal district.

Several years ago an unsuccessful attempt was made at hydraulic mining. A large dam was erected in the headwaters of the Corozal River and the water was conducted down by a 10-inch conduit to a point where the gravels were especially abundant in the same stream just above the town. Due to the difficulties in transportation, the cost of construction of the dam and conduit was very great, the material being brought some 20 miles from San Juan to Corozal by ox-cart and thence into the hills by pack. Unfortunately, the conduit proved inadequate to withstand the pressure of so large a head of water and soon went to pieces. The project was then abandoned for lack of funds and has never been reattempted.

Gold occurs not only in the Corozal and Negros Rivers, but is to be found in minute quantities in almost every stream of the district. It has been washed in paying quantities from the Plata, Mavilla, Naranjito, Unibon, and Orocovis Rivers, but its presence in these streams is so rare that no regular panning is practised.

AURIFEROUS QUARTZ MINES

South of Corozal, in the barrios Negros and Palos Blancos, some exploratory work has been done in an attempt to discover the lode or veins which might have been the source of the placer gold (see topographic map).

In the barrio Negros some of the old Spanish workings have been reopened in recent years, and two new shafts of shallow depth have been sunk in an attempt to discover a large vein. A so-called vein about three feet wide has been exposed. The country rock is highly weathered, but appears to be an andesitic tuff. On close examination the vein proves to be a silicified zone composed of many quartz veinlets and stringers, none of which is over a few inches in width. These veinlets carry the gold, and when bunched in large numbers are workable. Neither the quantity nor quality of the ore can be depended upon, for it is no longer workable when the quartz veinlets become scattered.

In the Palos Blancos mine the conditions are much the same, though this prospect has been more fully explored. The country rock is an andesitic tuff with associated intrusives. The silicified zone, or vein, is somewhat larger than in the other case, and has been followed by one tunnel some 180 feet. A fair grade ore could be concentrated, and one shipment was made to the States. Neither of the two prospects is now worked. The Palos Blancos mine might prove a success if properly developed and capitalized.

PLATINUM

Occasional particles of platinum are panned out with the gold from the placers near Corozal. The metal is called *plata* by the natives, who think it is silver. Although it sometimes occurs in quite appreciable quantities, the natives get nothing for it from the local buyers. The writer in purchasing the results of a day's labor from one of the native panners found that it contained, roughly, 20 per cent platinum: so in this particular case the platinum content, discarded by the native as valueless, was approximately as valuable as the gold, which locally brings only $12.00 an ounce. Such high percentages of platinum, however, are rare.

COPPER

In the barrio Pasto, on the west central margin of the San Juan district, several copper prospects were visited and examined. These are the easternmost of a group of similar prospects that occur south of Ciales. The others, extending beyond the boundaries of the district, were not visited by the writer. The country rock is an andesitic porphyry, which has been described and figured on Fig. 22. This porphyry occurs as a large instrusive extending out of the district on the west. In this intrusive the ore occurs as impregnations along cracks and fissures. Several of the prospects in this vicinity have been partially explored. The principal one was examined by an American mining company and one shipment of several tons was sent to the States for smelting. In this prospect the principal vein, or impregnated zone, is about four feet wide. This had been followed about 30 feet into the hill. It is intersected by several other similar veins of smaller size. It is evident that the porphyry has been fractured and subsequently was mineralized. The copper-bearing waters have followed these fractures and deposited in them the copper minerals, impregnating the neighboring porphyry for distances varying from a few inches to several feet. At the juncture of two of these mineralized fracture quite a showing of copper is developed. In the specimens collected malachite, chrysocolla, and azurite appeared in the greatest abundance. Cuprite and chalcocite are rare at the surface, but may prove more abundant in depth. No idea as to the extent and quality of these occurrences can be had without further exploration. The ore bodies that have been unearthed in the ditches and tunnels of former exploratory endeavors have been subsequently concealed by infalling detritus and dense vegetation, so not even an approximate estimate could be made as to the quantity of ore readily accessible. The inaccessibility of this region has discouraged all attempts at the development of these prospects. The topography is exceedingly rugged and the distance from all means of transportation is considerable. At present the ore must be packed down to the valley of the Manati, from whence it can be carted to the main road. If the transportation facilities are eventually improved, these copper prospects may be successfully worked.

LEAD

No occurrence of lead of economic value was found. A small quartz veinlet carrying galena was seen in barrio Magueyes, south of Corozal, but no other indications of the presence of this metal were found in the district.

MANGANESE

In the same locality a thin bed of psilomelane was seen. Its extent could not be determined, but it did not appear to be of enough importance to warrant exploration.

ROAD METAL

Road metal is abundant in all parts of the district. The Tertiary limestone is extensively used as such on all the roads that pass through the limestone belt. It is said that the purer beds of the limestone give a good quality of lime on burning, but the scarcity of fuel makes this industry impracticable. The tuffaceous sandstone at K 8, Comerio road, is quarried and used as road metal for the carretera for some distance.

In the interior the andesites and massive tuffs are used and, where accessible, the interior limestone beds are quarried for this purpose.

Building Stone

Many of the igneous rocks of the district that would make excellent building stones are not, and may never be, quarried, owing to the limited demand for such material and the difficulties of transportation. In San Juan, where the local demand is greater, the San Juan sandstone is used to some extent in the residential section, chiefly in building foundations, since it forms a pleasing contrast to the cement.

Guano

Bat guano is found in many of the caves. Large deposits have accumulated in the caves south of Aguas Buenas. These are locally used by the natives as fertilizer.

ILLUSTRATIONS

Cross-sections

Soon after the writer began the geologic study of the district, it became apparent that the structure of the older series was in greater part too complex to be shown in even moderate detail on a geologic map of small scale. It was decided then to supplement the map by a few more detailed cross-sections. Therefore, careful traverses were made across the district along definite lines, so that three cross-sections might be constructed showing to some degree the complexity of structure encountered (see Geologic Cross-sections, Plate IV). The data collected in each case have been projected upon a straight line. In this way the windings of the road or trail have been eliminated and the normal proportions and relative positions of the associated formations more clearly shown. The section through Bayamon and Comerio is the most complete and accurate because of the better and more continuous exposures. The other two sections are based upon occasional exposures and are therefore somewhat more generalized.

Maps

The difficulty of obtaining a map of sufficient accuracy on which the geology might be plotted was soon realized. Available maps, however well adapted they might be for other uses, proved to be so unsuited to this particular purpose that it became necessary to construct a large scale topographic map before beginning the study of the geology of the district. The accompanying map is the result. It was constructed by means of

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MAPS

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the plane-table and telescopic alidade, the contours being sketched in from aneroid readings. The main roads and streams are shown with some degree of accuracy, and a reasonably correct idea of the character of the topography can be had from the contours.

When one attempts to map an area of 500 square miles of country as complex geologically and topographically as Porto Rico, in a single summer, any great degree of accuracy is manifestly impossible. The subdivisions of the older series are necessarily somewhat arbitrary, for the members of the series, as a rule, do not maintain sufficient constancy to make close subdivision possible. Many of the division boundaries shown on the map are generalized or are compromises because there is a continuous gradation between some of the formations. Even the boundaries of the intrusives are obscure in much of the area. Some were located by single or widely separated exposures in districts of almost continuous soil cover. The dominant rock type is indicated, however, in each case and the approximate distribution and general trend and relative importance of the larger formational units are brought out by the different color patterns.

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THE GEOLOGY OF THE COAMO-GUAYAMA DISTRICT, PORTO RICO

BY EDWIN T. HODGE

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INTRODUCTION

LOCATION AND AREA

This report covers an arbitrarily bounded area, which occupies the south central part of Porto Rico,[1] and will be called the Coamo-Guayama district. This district occupies about one-eighth of the 3668 square miles belonging to Porto Rico and measures 23 by 20 miles. Adjacent on the north is another area, the side lines of which are a continuation of those of the Coamo-Guayama district. It is called the San Juan district and has been described by D. R. Semmes.[2]

PURPOSE OF STUDY

The purpose of the investigations made by Mr. Semmes and myself is to give a geological cross-section of a typical part of Porto Rico. In addition, I will describe in some detail the complex geological structure and the peculiar rock types of exceptional petrogenetic history; I will discuss the origin of the Coamo thermal springs, and attempt to present the data establishing the main events in the geological history of Porto Rico.

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[1] See Outline Map of Porto Rico, Volume I, Part I, p. 26.

[2] The Geology of the San Juan District, Volume I, Part I, pp. 33-110.

ACKNOWLEDGMENTS AND PREVIOUS WORKERS

The author is grateful for much assistance in the preparation of this report. The investigation was made possible by the generous support of the Porto Rican Government in co-operation with the New York Academy of Sciences. The rigors of tropical field-work were more than compensated by the uniform courtesy and exceptional hospitality of the citizens of Porto Rico. The author wishes to express his appreciation of the counsel and guidance of the professors of the Department of Geology, Columbia University, especially that of Dr. Charles P. Berkey. The laboratory investigation of this problem was conducted in the Geological Department of Columbia University.

Numerous travelers and scientific men have published observations on Porto Rico, among whom are the following: P. T. Cleve, Brig. Gen. G. W. Davis, W. Dinwiddie, M. K. Domensch, Amos K. Fiske, S. H. Hamilton, R. T. Hill, J. S. Newberry, H. C. B. Nitze, T. W. Vaughan, W. J. L. Wharton, H. M. Wilson and C. P. Berkey. With the exception of Berkey (1915, p. 69), none of the above more than briefly mention the Coamo-Guayama district. The reconnaissance study by Berkey cleared up the fundamental problems in this district, and the results of this work have been extensively used in prosecuting the present survey.

GEOGRAPHY

The distribution of the essential geographic features is shown on the Outline Map. The area includes the City of Guayama in its southeastern corner and the villages of Cidra, Aibonito, Cayey, Coamo and Salinas. A magnificent road enters at the northeastern corner and leads southwestward through Cayey, Aibonito and Coamo toward Ponce. At Cayey a branch road leads southeastward to Guayama. A narrow-gauge railroad and a wagon road traverse the coastal plain from west eastward to Guayama.

The area is divided into a northern mountainous part, which occupies about two-thirds, and a southern low coastal plain. The mountains are devoted to grazing and to coffee and tobacco culture. Large crops of sugar-cane are grown upon the coastal plain. The character of the drainage pattern is shown by the accompanying topographic map.

Because the island lies across the path of the prevailing trade winds, there is a great variation in rainfall in the various parts. The northern slope of the mountain ranges, where the moist trade winds are forced to rise, receives more than an abundance of rainfall. In the northwestern corner it is said to rain continuously week after week and the mountains at that season of the year are heavily clothed in mist. In contrast to this the southern coast, which is swept by winds deprived of their moisture, is extremely arid. Months frequently pass without a drop of rain falling, and during these periods all the vegetable life in areas not irrigated withers up and cattle must be driven to the interior. Because of the aridity an elaborate system of irrigation has been developed on the south coast, and to this all streams of the district contribute all or a part of their waters.

The harbors are poor and exposed. Aguirre is the best, but the approach to it is through a circuitous channel left by rapidly spreading mangrove swamps.

PHYSIOGRAPHY

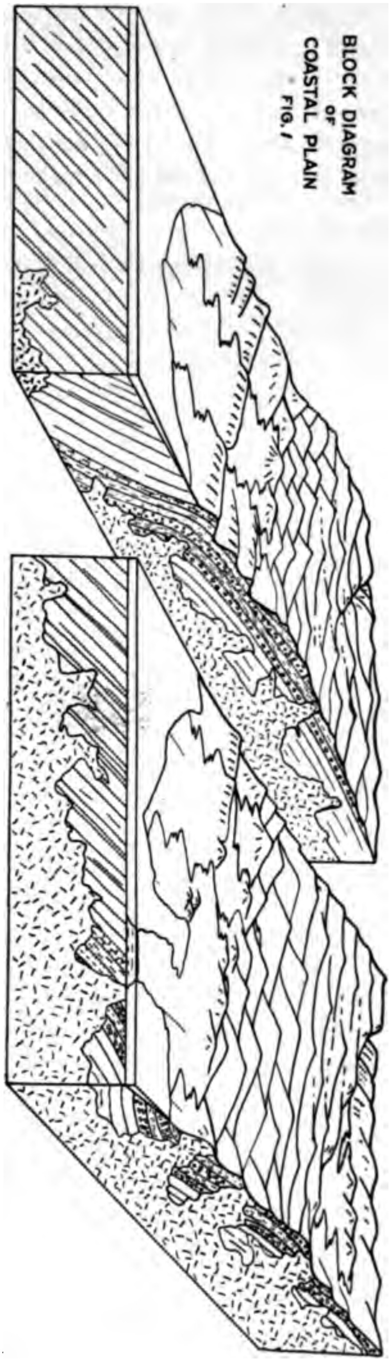
General Statement

Forming a southern border variable in width is a coastal plain which slopes gently upward from the shores of the Caribbean Sea to an elevation of about 300 feet. North of the plain is an old-land composed of a rugged mountainous interior with a main belt of mountains, known as the Sierra de Cayey, extending from the northwest corner of the district southeastward almost to the southeast corner. Because the old-land is dissected to maturity, broad sprawling spurs stretch southward and northward from the main range, and the mountains are not sharply separated from the plain, embayments of the latter extending northward between the spurs for many miles. Two major interior subsequent lowlands occur, one in the northeastern corner and the other forming a linear belt reaching northwest and southeast through the south central part of this district.

Coastal Plain

DISTRIBUTION AND GENERAL CHARACTER

The distribution of the coastal plain, which will first be described, is shown by figure 1. It has an average width of four miles. Guayama, Coqui and Salinas are located upon its inner margin. An embayment of the coastal plain into the mountains reaches a point where the Guamani River crosses the road, another reaches up the Salinas River to La Lapa, a third almost to Coamo and near the western border one extends almost to the Military Road.



BLOCK DIAGRAM OF COASTAL PLAIN

FIG. 1

The coastal plain slopes gradually toward the sea. At Guayama the elevation is 200 feet and at Coamo Springs it is 240 feet. This gentle inclination is broken by mendip hills which rise like islands above its general level, by wave-cut and river-built terraces, and by meandering and slightly entrenched streams. The slope, the fine alluvial cover, and the generally undulating character of the plain make it admirably adapted for sugar culture.

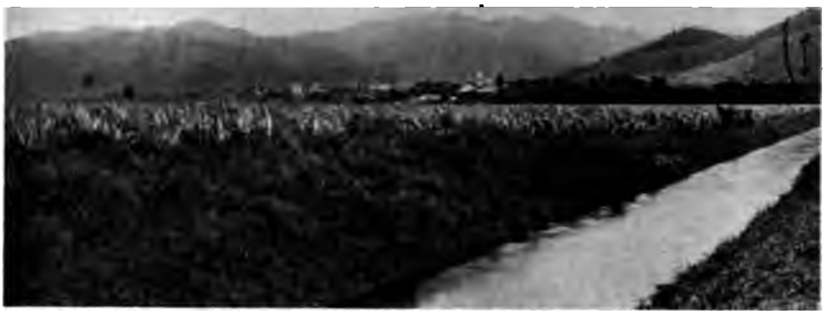


FIG. 2.—*Guayama upon the upper coastal terrace*

The arrows point respectively to the (1) lower and (2) upper terraces. Photographed by Professor Charles P. Berkey.

HILLS

The few mendip hills form prominent landmarks, such as the two large hills, 700 feet high, which lie just east of Guayama and are nearly surrounded by the coastal plain (Fig. 2). A group of low hills, the highest of which is 400 feet, occurs adjacent to the coast and west of Aguirre Harbor and are called Aguirre Hills. North of Aguirre Hills and west of Coqui is a low linear mound 300 feet high, known as Monte Sabater. There are two large hills occurring as detached portions of the inner mountains, one of which, north of Salinas, is 600 feet above sea-level and the other, just east of Coamo Reservoir, is 300 feet high. All of these are portions of the old-land protruding through the alluvial coastal plain.

Discontinuous linear swells of the coastal plain, 400 feet high, lie south of the mountainous tract and extend from Salinas River westward to the boundary of the district.

TERRACES AND SEA CLIFFS

Other features interrupting the general slope of the coastal plain are terraces and sea cliffs, of which two are well shown near Guayama, which is situated upon the highest of these terraces, 200 feet above the sea-level. The photograph (Fig. 2) shows very well the abrupt termination of the terrace against the Guayama Hills in a sea cliff. Ninety feet below, as indicated by the arrows, is the largest terrace, which descends by a gentle inclination to the sea.

Along the Rio Jueyes three sea cliffs are to be found. One occurs very near the coast, another a mile from the coast and the third, formed by the Cerro Raspado, occurs two and a half miles from the coast; the outer margin of the lower terrace is 35 feet high. The outer margin of the upper terrace is 100 feet higher than that of the lower. Traced eastward, both disappear before Salinas is reached, but both can be traced westward, though much dissected, to positions north of Santa Isabel. The upper terrace is well developed just south of Coamo Reservoir dam where its outer margin is about 160 feet above sea-level and rises to over 200 feet at Coamo Springs. The lower two terraces are much dissected. The southernmost part of the Aguirre Hills has a poorly developed sea cliff, which forms the nearest approximation to a clifted promontory found in this district.

COAST LINE

Aside from local irregularities the south shore of the Coamo-Guayama district has an angular pattern. Thus a wedge extends seaward to Pta. Equilarte; another to Pta. de Cayures; a third between Aguirre and Salinas; and a fourth south of Santa Isabel. Between each of these angular projections of land is an equally angular extension of the sea. This irregularity is due to drowning of the subsequent valleys which lie at angles to the coast line.

MOUNTAINS

DISTRIBUTION AND CHARACTER

The dominating range in Porto Rico is the Sierra de Cayey and it passes through this district from the northwest to the southeast corner. The Sierra de Cayey forms the divide for all the rivers in the Coamo-

Guayama district. Nowhere in this district is it cut through, but it has been maturely dissected, so that out from it to either side extend many sprawling ranges, some of which have been completely severed from the main range. Though its elevation in no place exceeds 4000 feet, nevertheless because of its ruggedness and heavy vegetable covering it is a most imposing and beautiful feature.

The Coamo Springs is a homoclinal range (Fig. 17) which extends from the west central border of this district, with a general southeastward trend, to Salinas Hill, just northwest of Salinas. Aguirre Hills are thought also to be related to the Coamo Springs Range and are so mapped in this report, though this relationship has not been proven. This correlation of the Aguirre Hills is based upon their alignment with the Cerro Raspado and upon the fact that they are formed of a limestone of similar character. The Coamo Springs Range rises as a solid, abrupt wall 500 to 1200 feet above the surrounding lowlands, having a steep northeastern slope and a gentler southwestern, with a width of about one-half mile. Its crest is notched by many wind-gaps and it is cut through by several large superimposed rivers, which serve to divide it into divisions as shown by the topographical map. South of this range lie many smaller and lower hills created by the erosion of subsequent valleys by tributaries of the Coamo and Descalabrado Rivers.

HEIGHT, RELIEF, DISSECTION

The average elevation of the Sierra de Cayey is 2500 feet in the eastern and 3000 feet in the western portions of this district. The relief of all the ranges is, perhaps, 1500 feet. The surface is dissected to early maturity and the texture in the interior is exceedingly fine. The slopes of the Porto Rican Mountains are always steep and deeply dissected. Thus slopes of 40° are common. The mountain sides are always cut by numerous gullies producing a very fine texture. Knife-edge crests are common and are barely wide enough to give footing to the small Porto Rican pack-horses as they follow the trails upon them. The cause of these knife-edge crests is the character of the soil, which will stand up as vertical walls 5 to 10 feet for a year or more without caving. Such a soil does not creep readily after streams have cut the slopes, but remains standing upon the divides until finally carved away by running water. Headward portions of streams on opposite sides of divides, therefore, are not separated by a zone where soil flowage assists, but erode until they actually meet in a knife-edge divide.

CONCORDANT ELEVATIONS

The peneplane described by Berkey in his reconnaissance study of Porto Rico in 1914 is well shown in the Coamo-Guayama district. As one stands in the lowlands and looks up to the summits, it seems impossible to imagine any surface more broken or any slopes more steep. Viewed from a summit, the peaks blend into a solid mass with a remarkably level horizon line, regardless of the direction in which the distant peaks are viewed. Not only are the mountains in the interior of nearly uniform height, but some of them have flat tops, which often afford sufficient space for a half dozen native huts. When one considers that the mountains are composed of rocks of almost infinite variety and exceedingly variable structure, their concordant elevation and the existence of an occasional flat area argue that the whole mass has been beveled by erosion to form a peneplane surface (Figs. 3 and 7).

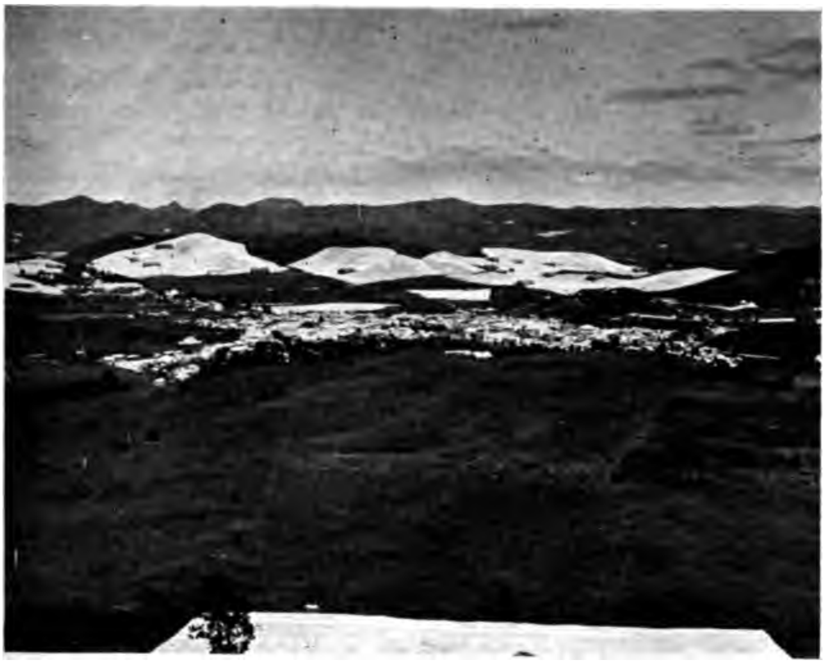


FIG. 3.—*Cayey in the Barranquitas-Cayey Lowland*
Photographed by Professor H. E. Crampton.

INTERIOR VALLEYS

There are two large subsequent valleys of greater importance than any other in this district. The Military Road from Ponce to Albonito follows a great lowland which continues eastward into the area under consideration. If one could remove the Coamo Springs Range, at the point where both the Military Road and the Rio Descalabrados find passage, this valley would continue eastward to the Coamo River. East of this passage or gap the valley is very large and open. It extends eastward from the great white hills of the Coamo Springs Range lying just outside the western boundary of this district to a mile beyond Coamo Springs. The southern boundary is formed by the wall-like Coamo Springs Range and the northern boundary is not sharp and distinct, but changes gradually from a flat lowland through many small hills to a large and low range. Beyond Coamo Springs and a group of low hills 400 feet above sea-level it continues eastward and finally merges into the valley of the Salinas. The floor is uniformly 300 feet in elevation.

The largest lowland, carved in soft tuffs and limestones, is found north of the Sierra de Cayey, in the northeastern part of this district. The shape is irregularly ovate, with the apex pointed toward Aibonito and the base widening northward so as to include Cidra. The principal outlet is north of Comerio, where the Rio de la Plata has cut a deep gorge in the highlands to the south. Another low pass or col lies beyond Las Cruces and it is taken advantage of by the Military Road between Cayey and San Juan. The floor is not flat, but is broken by numerous low hills composed of resistant rocks which rise as much as 300 feet above the general level and have a trend conformable with the lowland as a whole. The average elevation is 1500 feet above sea-level.

DRAINAGE

RELATION OF STREAMS TO TREND OF VALLEYS AND MOUNTAINS

The larger streams do not lie in the larger valleys, nor are the major ranges parallel to the larger streams. This feature indicates a superimposed condition of the larger streams and the development of large subsequent valleys by their tributaries. A portion of the Rio de la Plata is an exception to this rule, for it descends from the northern slope of the Sierra de Cayey and flows northwestward across the floor of the Barranquitas-Cayey lowland to Comerio, where it turns northward and escapes through a narrow gorge. On the other hand, the Rio Descalabrados, the Coamo and the Rio Jueyes cut narrow water gaps through the Coamo Springs Range. Related to the gorges through the mountain are gaps through which streams do not always flow; for instance, the Cerro Raspado is cut at its eastern extremity by a deep notch through which a road leading northwestward from Salinas passes to the lowlands lying behind the range.

The width of the stream valleys is directly related to the character of the rock over which they flow. Where the streams flow across lowlands, their valleys are wide; where they flow through ranges their valleys are narrow. There are also minor variations in width which apparently are due to variations in the character of the rock over which the stream flows. Some of the streams flow over broad, flat-bottomed, loam-covered valleys for perhaps a maximum distance of half a mile and then cut deep gorges beyond which they may develop plunge pools. This condition is repeated many times in the length of every stream. It is only possible to give a few illustrations of the innumerable cases. For instance, three miles north of the Rio Jueyes Water Gap the Rio Jueyes cuts a gorge not more than 10 or 15 feet wide, while just beyond this gorge a valley one-quarter mile wide and over 3000 feet long opens up. Just beyond the open valley occurs another constriction and then another wide valley. In the gorges the stream flows on bare rock and through the wide valleys upon thick beds of silts and pebbles.

ENTRENCHED STREAM TERRACES

Near the inner margins of the coastal plain all the streams are more or less entrenched. Thus the Coamo River, near Coamo Springs, cuts vertically downward into alluvium (Figs. 1 and 23). Other streams are similarly incised, but to a less extent; the degree of incision seems to decrease eastward.

The streams which show the best entrenchments also show the best terraces; thus, on the Rio de Coamo three excellent terraces are developed. All the larger streams are provided with terraces, but the smaller streams lack them. The largest number of terraces cut, one below the other, is three, and these are found near the Baños de Coamo. The terraces are always local, yet the higher terraces are sometimes very wide, as, north of the Coamo Reservoir, along the whole lower half of the Descalabrados, the Jueyes and the Rio de La Lapa.

COASTAL STREAMS

Streams which flow across the coastal plain are modified in various ways. Many of the streams meander, others wither away and practically disappear; the Salinas is an excellent example of this latter phenomenon.

Long before the coastal plain proper is reached this stream takes on a braided appearance and by the time it has gone a short distance beyond Salinas it disappears in the soft porous alluvium. Some streams, of which the Cimarrono is the best example, exist only on the coastal plain.

CAPTURE

The Salinas wind gap mentioned above is a good example of recent capture. At one time a stream must have flowed through this gap to the Caribbean Sea; indeed, a small brook is developed there now in very wet weather. Water-worn gravels occupy this gap. Apparently a subsequent branch of the Rio Jueyes has captured the headward portion of the stream which formerly occupied the gap.

GENERAL GEOLOGY

Difficulties in Obtaining Data

Geological data are not easily obtained in the Coamo-Guayama district. Contrary to a generally prevailing belief, the larger part of Porto Rico is not readily accessible. Aside from the excellent roads which pass through the Coamo-Guayama district, travel in the mountainous interior is over miserable trails where one must often hew his way with a machete. In addition to the difficulties of penetrating the thick tropical growth, there are the difficulties resulting from the heavy mantle of soil. Outcrops are so rare that in field-work it was necessary to wade the streams and examine the rocks laid bare in the stream bed. Exposures in the streams, in the cuts along the Military Road, and the occasional outcrops at the crest of the mountains form the chief sources of the information contained in this report.

General Physical Character of the Rocks

The greater proportion of the rocks of the Coamo-Guayama district are of sedimentary origin and consist of tuffs, agglomerates, shales derived from volcanic ash, conglomerates, limestones and cherts. The tuffs and conglomerates are decidedly massive and the determination of their dip and strike is impossible. The conglomerates show little or no bedding. Occasional beds of limestones, shales and cherts furnish the only clews as to the geological structure of this terrain.

The types of rock derived from volcanic sources dominate and of these few have passed through more than one sedimentary cycle. For the most part, the sediments are loosely bound tuffs, ash shales, or calcareous tuffs. Despite the fact that the igneous rocks are quantitatively negligible, yet they are of great scientific interest because dikes, sills and flows occur in almost infinite number. If all the igneous outcrops which have been observed were plotted on the accompanying geological map, the entire surface would be dotted, and for that reason only a few of the major igneous bodies have been mapped.

Another factor adding to the complexity is the rapid alternation from one type of rock to another. For instance, in traversing a stream for a kilometer some fifty different and distinct occurrences of igneous and sedimentary rocks may be observed. In the few places where it was possible to trace a definite stratum laterally its character changed so completely that specimens collected a mile apart would not be recognized as belonging to the same bed. Occurring just as often as the above changeable transition is the pinching out of the strata because of their lenticular shape. It is, therefore, no exaggeration to say that the Coamo-Guayama district in particular and Porto Rico as a whole consists primarily of volcanic ash in many thousands of sedimentary beds, in part reworked and in part alternating with marine strata, all of which are cut through and through in a most varied manner by igneous rocks.

General Structure

The grouping together of such varied rocks into formations would not be such a difficult matter if the structure were simple and if it were possible to gather more complete data concerning the structure. Tropical vegetation and deep residual soil conceal the bedrock. It was the experience of the author and of several other geologists who have worked in Porto Rico that frequently in the course of a whole day's traverse only one dip and strike could be obtained which were considered reliable.

Such conditions explain why the structural relationship of the bedded rocks in the Coamo-Guayama district are not well understood.

In the western half of the district all of the dips recorded were to the south and varied between 20° and 55°. The fact, that the dips in the older series are not in all cases steeper than those of the younger, indicates local folds; nevertheless, because of insufficient outcrops, it was impossible to determine the detailed character of these local folds. Eastward, approaching the borders of a batholith which lies just beyond this area, more variable dips were noted. Aside from local irregularities, it appears that most of the northern half of this district is folded into a flat, broad syncline. The south limit of this syncline begins to develop at K. 12 on the road to Guayama. South of this point to K. 24 the rocks are folded into an anticline. Between K. 24 and the south edge of Guayama another narrow syncline is developed.

The above described major folds are highly modified by local variations, such as the gentle flexures or even close folds approaching contortions. The strike of all the strata is northwest. In the eastern third the average strike is N. 70° west, and in the western two-thirds the average strike is N. 50° west.

Crushed zones are universally present, but it is rare to find an accompanying displacement. Nearly every Porto Rican rock in thin section or in hand specimen shows one or more periods of fracturing; these minor breaks must be related to major fractures, and it seems safe, upon this evidence, to say that faults are numerous and some of them probably have great displacement. Only two major faults were observed. One which has a north trend, and by a downthrow on the east side, offsets the ends of the Coamo Springs limestone at the Rio de Coamo Water Gap and probably determines the course of the Coamo River through the limestone at this point. Another fault cuts obliquely through the Coamo Springs limestone west of the Descalabrados Water Gap. This fault is aligned with faults found in limestones to the south of the Coamo Springs limestones and to the east of the Descalabrados River, and all are undoubtedly parts of the same fault. The downthrow side of this fault is also to the east. The faults affect all the rocks and may be quite recent, but the folds are certainly much older. The greater age of the folds is indicated by the fact that the Arecibo limestones have a very gentle dip to the sea, that the recent alluvial beds are horizontally bedded, and that both lie unconformably upon the older folded rocks.

Sedimentary Types of Rock

TUFFS

From whatever viewpoint Porto Rico is considered, the conclusion is always that the island is largely and essentially a heap of volcanic débris. Volcanic fragmental rocks alone or volcanic fragments, occurring as constituents of rocks of subsequent deposition, form the greater bulk of all the sedimentary types. These fragments are principally augite-andesite: no hornblende andesites and few olivine basalts were observed. In these igneous fragments the feldspar phenocrysts are prismatic andesine oligoclase, highly altered to calcite, chlorite, hematite and laumonite. The augites are equant, pale green, and highly fractured but very fresh. The groundmass consists of the same components and is, as a rule, profoundly altered to the secondary minerals mentioned above. Magnetite is present in variable proportions.

Doubtless these minerals are the accumulations from long-continued explosive volcanic action, and their habit and associations give the only clew we have of the former physical conditions.

VOLCANIC BRECCIAS

The true volcanic breccias are of very great variety. The colors of the constituents are green, red, purple, black, gray, brown, buff and white; but green is most common. Sometimes all of these colors appear in a single hand specimen, and where such a rock outcrops in a stream bed and is highly polished by stream erosion a very beautiful effect is produced. The green is due to chloritic alteration, the red and purple to hematite, the black and gray to unaltered shales or limestones included among the volcanic components, the buff and yellow to limonitic alterations, and the white to calcite. Rock types represented by the fragments are chiefly augite andesite with rarer olivine basalts and palagonites. The textural varieties are so great that it is common to find as many as fifteen textural types of augite andesite in a single thin section. The cementing substances are, as in the tuffs, chiefly calcite and chlorite with some iron oxides and frequently zeolites, such as laumontite and natrolite. In addition to the volcanic breccias accumulated under æolian agencies, two other types of breccias are very common. Both are flow breccias. One type is a lava flow, the crust of which first solidified and subsequently became brecciated by the continued movement of the lava. The other and more common type is a lava flow into which, while still fluid, fragmental material was dropped or which picked up fragments in its course.

AGGLOMERATES

Highly angular agglomerate boulders are very rare. Most of them show some rounding either by stream action or by mud flow, and the frequent occurrence of lenses of rock, consisting of subangular boulders in a matrix of tuff, suggest that mud flows were common.

CONGLOMERATES

Conglomerate lenses are very common in the midst of other rocks. Their lenticular shape, lack of persistence along the strike and occasional fluvial cross-bedding indicate that they were accumulated as torrential fans. Some of the conglomerates have an igneous matrix which was formed as a subsequent injection into the ready-formed conglomerates.

SHALES

The shales consist of bedded ashes and reworked tuffs. The former have suffered so little reworking that in thin sections their pyroclastic nature is easily made out. The latter have been so thoroughly disintegrated and sorted by water that the original character of their material is determined only by a few associated volcanic fragments. The perfection of the bedding is best developed in the younger rocks and most of the shales were accumulated near the shore, as is indicated by the presence of organic remains in them. Some of the shales are silicified and others are epidotized. The silicified shales are thought to be due to the organization of radiolaria and diatoms, and the epidotized shales to hydrothermal influences.

LIMESTONES

Between tuffs with a few organic remains and limestones with a few tuff fragments, there is every graduation and in like manner the limestones are related to the shales. Some of the tuffs, andesitic sills, and andesitic flows have so thoroughly altered to carbonate that they now consist of as much as 80 per cent carbonates and have usually been mistaken for limestones. The true organic limestones can be divided into two classes, those with no algal content and those containing algæ, and the latter are found only in the middle of the uppermost group of rocks. The other limestones are made up chiefly of foraminifera with some contributions made by pelecypod or gastropod forms. In all cases the bulk of the rock consists of reorganized calcite derived from organic remains.

TYPES OF IGNEOUS ROCKS PRESENT

Although the range of igneous rocks is wide (Figs. 24 to 40), the most common variety is augite andesite. The following list shows the range: rhyolite, granite, biotite granite, feldspathic andesite, granodiorite, augite andesite, hornblende andesite, diorite, hornblende diorite, hornblende-augite andesite, basic augite andesite, olivine-free basalt, and olivine basalt. Porphyritic rocks are uncommon and granitoid types extremely rare. The massive rocks appear usually in small dikes and flows; especially vesicular varieties were only observed in a few places. As pointed out above, the tuffs, volcanic breccias, and agglomerates contain so many igneous types that in a thin section of a tuff as many as ten to fifteen varieties may be observed. These fragments consist of rhyolites, feldspathic andesites, augite andesites and olivine andesites, and of these, as in the larger masses, augite andesites greatly predominate. After the augite andesites, feldspathic andesites occur in greatest abundance, and are followed, in point of number, by the basic varieties. The fact that the same type of rock appears in tuffs, flows, dikes and sills strongly suggests that these formations are nearly contemporaneous and indicates that while tuffs and breccias were accumulating on the surface liquid matter was being injected into the basal portion of the pyroclastic and sedimentary series.

HYDROTHERMALLY ALTERED AND MINERALIZED ROCKS

Nearly all the rocks studied in the Coamo-Guayama district show some mineralization and many of the rocks are intensely hydrothermally altered.

BASIS FOR AN ATTEMPTED DIVISION OF THE ROCKS

The rocks of the Coamo-Guayama are very hard to classify into series because of the variety of outcrops, complexity of the structure, extreme variability of rock types, and absence of fossils. The few fossils which have been observed are of no assistance in making correlations within this district, although they are of value in giving a clew as to the general age of the strata. The only practicable method of making correlations, which is not free from possibilities of error, consisted in noting the outcrops with their occasional dips and strikes; then, with a knowledge of the general structure, the hand specimens were compared and the outcrops of the same kind connected. Because of the similarity of the type, the divisions, except in a very few cases, between one series and another, are simply arbitrary lines, which attempt to separate sedimentary rocks of one general dominant character from those of another. While the correlations within the district are lithological, the ages of the various series rests upon a firmer foundation. Thus the structural data is sufficient to work out the succession and so determine which are the older and which are the younger. Again, there is some evidence of unconformities indicating diastrophic breaks of magnitude, and it may be fair to correlate these breaks with similar ones occurring at the same time in other parts of the world. Finally, there are fossils which indicate rather closely the age of the particular stratum in which they occur. Thus, with a known sequence of rocks, broken by a few unconformities, and with an occasional stratum, the age of which is more or less definitely known, it is possible to divide the rocks into major series.

The following series of sedimentary rocks, named after type localities from the northeast to the southwest, have been established:

Rio de la Plata series.
    Mostly tuffs with a few agglomerates, shales and limestones.
Barranquitas-Cayey series.
    Mostly shales with much limestone and a little tuff.
Sierra de Cayey series.
    Mostly conglomerates with a little tuff and some shale.
Guayama series.
    A complex series, mostly of shale, but with much chert, some tuff, limestone and conglomerate.
Rio Jueyes series.
    A complex series, mostly limestone, but with much shale and some tuffs and conglomerates.
Coamo Springs series.
    A heavy bedded limestone.
Rio Descalabrados series.
    A thick series of shales with a little limestone and chert.
Arecibo formation.
    Mostly limestone.
Santa Isabel series.
    Mostly alluvia.

And the following intrusive series:

Early intrusives.
Batholithic rocks.
Later intrusives.

In many cases the above divisions are areal and descriptive rather than distinctly stratigraphical.

RIO DE LA PLATA SERIES

The rocks comprising the Rio de la Plata series are named from the river whose headwaters flow across them for many miles. The series is composed chiefly of tuffs with a few agglomerates and several lenses of limestone. The tuffs weather rapidly and are easily eroded. Into them the Rio de la Plata has eroded a great lowland (Fig. 3). The formations composing this group form a broad belt which occupies the northeastern portion of the district, and structurally forms the flat crest of an anticline. The strike of the rocks is generally N. 40° W. The northern limit of this series is presumed to lie outside of the Coamo-Guayama district. No definite line can be indicated at its upper contact because the variety of rocks characteristic of the group changes by an insensible graduation into those classed as the Barranquitas-Cayey series.

TUFFS

Tuffs make up the greater part of this group and are, as a rule, unstratified. They vary from cream yellow to red, are frequently mottled, and weather easily to a sticky clay soil. The structural details of some occurring at K. 65 on the Military Road, west of Cayey, are shown in figure 4. Microscopically they are chiefly lithic tuffs. The fragments are either augite andesites or augite-olivine andesites. The augite occurs as fresh, fractured, embayed zonal crystals frequently surrounded by borders of magnetite grains. Augite, as phenocrysts, comprises about 10 per cent of these tuffs. The feldspars, which are of the oligoclase-andesine variety, are frequently embayed by the groundmass and largely altered to chlorite and calcite and comprise about 50 per cent of these tuffs. A few olivine crystals were present, but are now entirely altered to serpentine, magnetite, limonite and iddingsite. The groundmass is composed entirely of alteration products, such as calcite and limonite and a little pyrite. The lack of bedding and the angular character of the fragments indicate that these tuffs accumulated directly from volcanic eruption without any process of reworking.

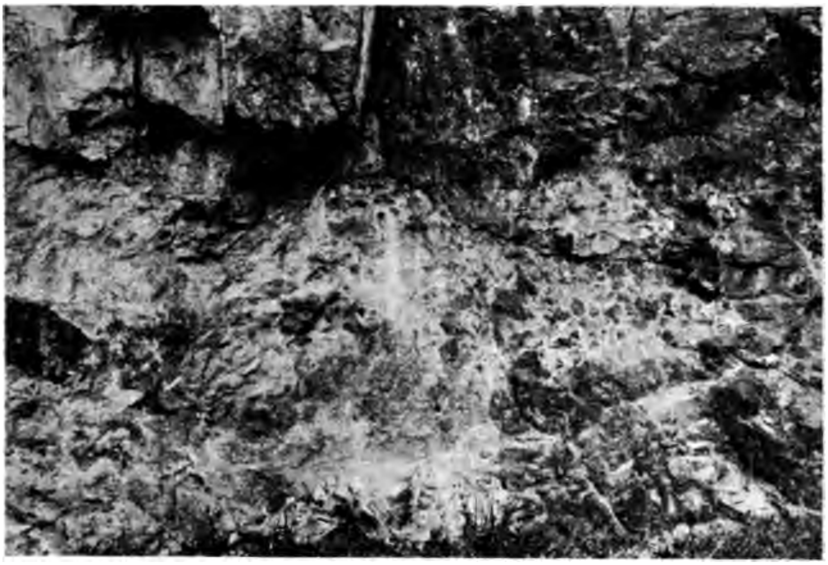


FIG. 4.—*Tuff beds*
Photographed by Professor Charles P. Berkey.

LIMESTONES

Two beds of limestones have been observed. One begins just south of Cidra and outcrops every two or three miles till just south of Comerio. It is a dense, light gray, fine-grained rock. The microscope proves it to be composed of numerous flat fragments of pelecypods and gastropods. The shells are triturated and oriented, showing that they have been wave-rolled and finally deposited in a bedded condition. Among the foraminiferal forms observed were:

Textularia gibbosa, d'Orbigny.
Textularia conica, d'Orbigny.
Textularia tiochus, d'Orbigny.
Plecanium (*Textularia*) *speyeri* (Reuss)?
Operculine sp.
Orbitoides papyracea.
Orbitoides faujastii, Sowerby.

The shells make up about 60 per cent of the rock and the matrix is composed of crystalline calcite, recrystallized from the shell fragments and their detritus. A second small lens of limestone, of essentially the same character, occurs about three miles due south of Cidra.

AGGLOMERATES

Thin beds of rock, composed of angular or rounded andesite or of augite andesite prophyry boulders varying in diameter between 1 to 6 inches, appear frequently as lenses in the tuffs. Where the boulders are angular they are undoubtedly agglomerates and where rounded they exhibit the effects of transportation, probably in mud flows. The matrix of both types is always tuffaceous.

Barranquitas-Cayey Series

The rocks of the Barranquitas-Cayey series are respectively named from the two villages situated upon them, in the northeast corner and in the eastern margin of the Coamo-Guayama district. The series extends from the north central part of this area southeastward to the east central border and forms a belt averaging about three and one-half miles across the outcrop. This group consists chiefly of shales and shaly limestones with numerous limestone lenses and an occasional bed of tuff and conglomerates. The anticlinal structure of the Rio de la Plata series changes in its southern margin to an equally flat syncline. This syncline continues southward and gives the structure to the Barranquitas-Cayey series. The dip of the southern limb of the syncline increases in steepness to the southward until, near the upper contact with the Sierra de Cayey series, the dip amounts to 30° to 40° N. The strike of N. 40° W. in the western part changes to almost due east in the east-central part. Subordinate to the major structures are several faint anticlinal flexures, especially in the northwest near Comerio. The thickness is between 2000 and 3000 feet. The lower part grades into the Rio de la Plata series and the upper portion forms a sharp contact with the Sierra de Cayey series.

SHALES

The shales grade on the one hand into massive tuffs and on the other into pure limestones. The majority are calcareous and the change from argillaceous shales to calcareous is very gradual. Some of the shales are siliceous, as, for instance, several of the gray members which extend uninterruptedly from Barranquitas to Aibonito. The color varies from light gray and green to a very dark gray, almost black. The bedding averages two to three inches. The rocks break very easily into rhombs about five inches long. The siliceous varieties under the microscope prove to be very dense, streaky shale, containing about 20 per cent of tiny spherical areas, averaging 2 mm. in diameter; a few of these are filled with silt and most of them are empty, but in one was found a radiolarian belonging to the genus *Lithocampe*, so that it is reasonable to suppose that they are all due to foraminifera which have been dissolved

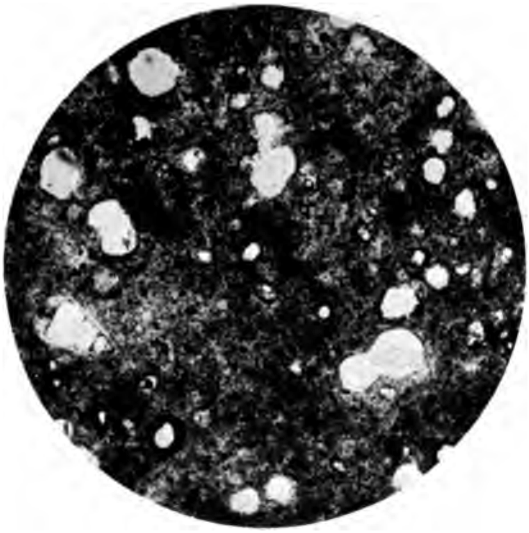


FIG. 5.—*Lithocampe sp. in shales of the Barranquitas-Cayey series*

out (Fig. 5). The chalcedonic cement of the rock may have been derived by recrystallization of the siliceous *Lithocampe* shells. Some of these shales are intensively mineralized by pyrite which has come in along bedding planes and has metasomatically replaced the shales.

LIMESTONES

Beds of limestones occur frequently among the shales, and of these three are of special importance. A series of interbedded lenses occur near the base of the series and outcrop frequently along the road from Cayey to Aibonito. They are black or dark gray in color and very dense, and when examined microscopically are found to consist of innumerable round bodies about 3 mm. in diameter, which are varieties of radiolarians and diatoms. The diatoms are:

Paralia (*Melosira*) *sulcata,* Ehr.
Consccnodiscus elegans, Grev?

And the radiolarians are:

Porodiscus concentrica (*Flustrella concentrica,* Ehr.) (Fig. 41).
Lithocampe sp. (?) (Fig. 5).

The tiny shell bodies are all stratified and about 30 per cent of them have been recrystallized to form an interlocking crystalline of cement calcite. Occurring in streaks and parallel with the bedding in these rocks is about 5 per cent of carbonaceous matter. There are also many angular crystals of augite and feldspar which are altered to calcite. It is evident that these limestones were formed either in the neritic zone or upon land by a gradual accumulation of foraminiferal, diatom, and radiolarian shells which had drifted landward and that, as they accumulated, wind-borne pyroclastic fragments were dropped among the shells and so added to the limestone. These limestones are, therefore, recrystallized tuffaceous shell limestones.

Another limestone occurs near the middle of the formation two and one-half miles south of Cayey. This limestone varies from a dirty gray to a dull purple in color, and the microscope shows it to be composed of shell fragments. The fragments are bounded by curves which are not in harmony with the organic structure and which indicate that the components have been rounded by erosion. This wear was developed under oxidizing conditions, as is shown by the heavy hematitic stain bordering each fragment and the entire absence of this stain in the interstitial cement which is pure calcite of secondary origin. The rock also contains some introduced sulphides. Apparently shells were blown from the strand inland and accumulated in beds. *En route* they were worn and oxidized and subsequently they were cemented by calcite, introduced probably by the agency of rain waters (Fig. 6).

Another heavy belt of limestones, "The Mountain limestones" of R. T. Hill, occurs close to the upper contact of this group and extends in a belt from about one mile west to six miles east of the Military Road. It is estimated to be a thousand feet thick.

The relationship between the shales and the limestones is very intimate. The former accumulated as estuarine, delta, or mud-flat deposits, the latter either just beyond them in the neritic zone or upon them where shells were wind-drifted inland a short distance. The shales contain many marine organisms and the limestones much terrestrial material.

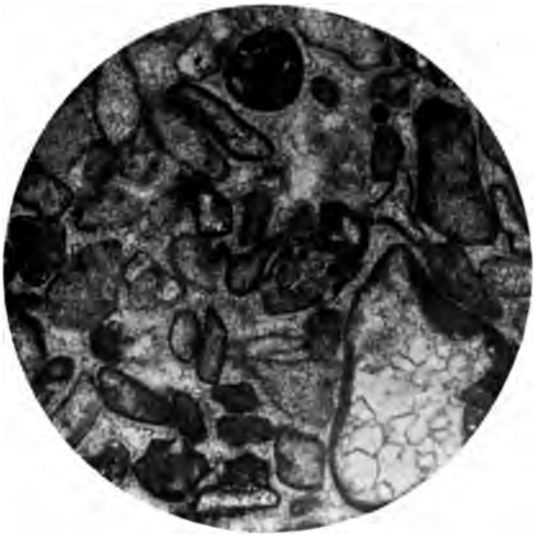


FIG. 6.—*Shells worn, oxidized, and cemented together to form one of the limestones of the Barranquitas-Cayey series*

TUFFS

The western two-thirds of the Barranquitas-Cayey series is chiefly shales, but in the eastern portion a tuffaceous phase develops until, at the eastern border and beyond, the series is composed of tuffs with a few agglomerates. A similar gradation exists between the tuffs and limestones or shales. Some are very fine grained and would be called shales in the field but for an occasional grain indicating a pyroclastic origin. The tuffs vary from the texture of ashes to volcanic breccias and coarse agglomerates. The color is black, dark gray or olive green; where fine grained, and, as the texture becomes coarser, the color becomes mottled because of the fragments, which may be black, gray, green, dark purple or dull red. Many of the lava flows contain tuffaceous material which may amount to as much as 40 per cent. Under the microscope the tuffs prove to be divisible into two classes, crystal tuffs and lithic tuffs. The crystal tuffs (Fig. 12) have the composition of an augite andesite porphyry and contain, taking the average, about 20 per cent augite, 40 per cent andesine feldspar, 20 per cent magnetite and 20 per cent of secondary products.

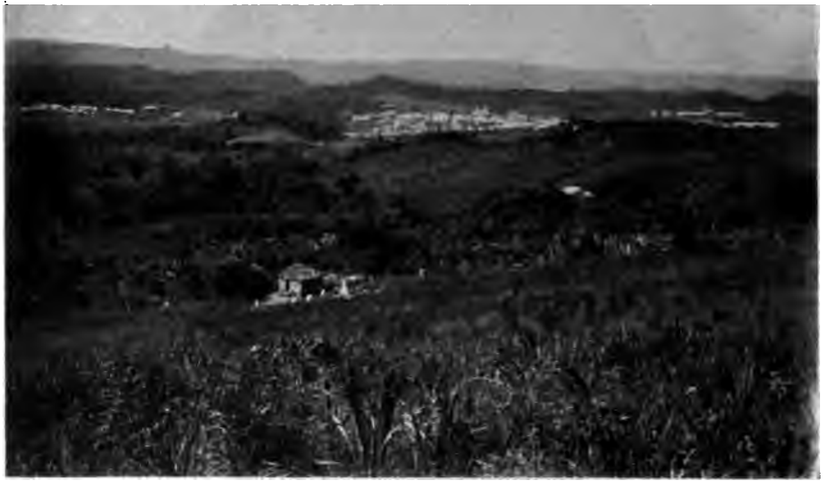


FIG. 7.—*Topography of the Barranquitas-Cayey Lowland*
Photographed by Professor Charles P. Berkey.

Sometimes they show a faintly streaked character, as if they were deposited under some sedimentary control. The augite is fresh, fractured, and pale green. The feldspars are highly altered, usually to chlorite and some epidote, which have, by their development, created the binding material of the rock. At times there are small pseudovesicular spaces filled with zeolites, probably natrolite. These spaces are about 1 mm. in size and are probably produced by infiltration and metasomatic replacement by zeolites.

In composition the lithic tuffs (Fig. 13) are rather simple. They are usually composed of feldspathic andesites or augite andesites. The textural types, however, are numerous and as many as fifteen may be present in one thin section. They vary from glasses to felsites of many textures and structures.

PHYSIOGRAPHIC EFFECT

The shales of the Barranquitas-Cayey are more resistant to weathering than the Rio de la Plata group. The spurs which extend out from the Sierra de Cayey are carved in them. Other hills occur in the lowland, such as the Cerro Gardo and Cerro Rabanal; their occurrence is due to the presence of more resistant shales. The topography thus produced is illustrated in figure 3. In this picture the greater part of the foreground, extending beyond the village of Aibonito, is occupied by the Barranquitas-Cayey group and beyond the first crest is the lowland cut into the Barranquitas-Cayey series.

GENESIS

The composition of the formations and their succession gives some clew as to their origin. Apparently at the time that the Barranquitas-Cayey series was being formed a volcanic center existed to the northeast and furnished the larger part of the material of the strata. In its immediate vicinity the sediments were mostly pyroclastic in origin. Farther away the volcanic ejecta were reworked and deposited close to the shore of the Caribbean Sea. The offshore zone was almost outside of volcanic influences and in it strata of biogenic origin with slight addition of pyroclastic material were chiefly accumulated. Compared with the Rio de la Plata series, which was formed during a period of intense vulcanism, in which there were a few quiescent intervals sufficient for a slight invasion of the sea, the Barranquitas-Cayey series is formed largely of reworked material indicating distant or less violent vulcanism.

SIERRA DE CAYEY SERIES

DISTRIBUTION

The rocks of this series are mostly conglomerates, with a few tuffs, and are found cropping out along the crest of the Sierra de Cayey Mountains, after which they are named. The road from Barranquitas to Barros, beyond K. 16, follows the lower contact of the Sierra de Cayey series with the underlying Barranquitas-Cayey series. The bends of this road, which swing northward, are upon the shales of the Barranquitas-Cayey series; those which swing southward expose the conglomerates of the Sierra de Cayey series. The Military Road between K. 85 and K. 88 crosses the Sierra de Cayey Range through a wind gap carved in this conglomerate.

The conglomerate is well shown north of La Lapa, where the Rio Cayey cuts a narrow gorge, and again where the Jajome cuts through it west of Jajome bajo. The conglomerate phase is not dominant in all parts of this series. In the eastern portion tuff occurs instead of the conglomerate and for this reason the Cayey-Guayama Road between K. 15 and K. 21 shows comparatively few exposures of conglomerates. This transition from conglomerates to tuff is excellently shown along the trail, which leads from K. 21 westward to Barrio del Carmen.

STRUCTURE

The synclinal structure found in the Barranquitas-Cayey series changes to anticlinal in the area of the rocks of the Sierra de Cayey series. Thus,

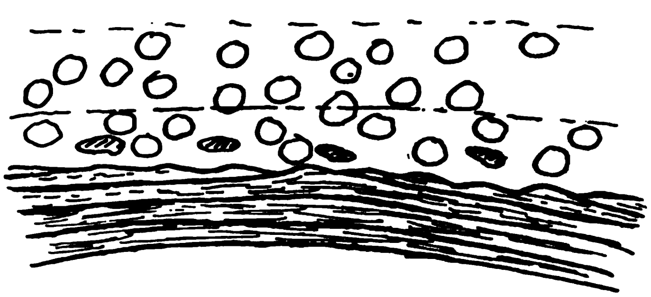


FIG. 8.- *Character of the unconformity between the Barranquitas-Cayey and the Sierra de Cayey series*

a flat anticline exists between kilometer 15 and kilometer 24.5. Going westward the strata begin to dip uniformly southward at angles between 30° and 40° and the strike varies between N. 40° to 60° W. A break of importance occurs at the base of this series, as indicated by the great conglomerate beds in the Sierra de Cayey group and by a distinct unconformity visible at two places. Thus between K. 86 and K. 87, on the Military Road west of Aibonito, the basal conglomerate of the Sierra de Cayey group rests upon the eroded surface of the underlying shales and contains pebbles of these shales (Fig. 8). Dips taken along this section show the shales to be gently folded and the conglomerate to lie upon the truncated portion of a faint anticlinal fold. Again, just west of where the Rio de Cuyon changes from a southward-flowing to an eastward-flowing stream, the heavy conglomerate lies upon a truncated portion of an anticlinal fold in the underlying shales. The upper contact is gradational with the overlying series. The formation is estimated to be between 3000 and 4000 feet.

COMPOSITION AND CORRELATION

The series is composed almost entirely of conglomerate with a few assorted beds of tuff. The basal portion lies unconformably upon the older formations, as shown by evidences both of erosion and folding before the conglomerate beds were deposited; and the upper portion changes by a gradual gradation into shales. Beds of shale begin to appear at infrequent intervals in the conglomerate, and then become more frequent, until shales finally constitute the entire group. Beginning where the shale beds predominate, another series, called the Guayama, is established.

CONGLOMERATE

The pebbles and boulders vary greatly in size, from a tenth of an inch up to seven feet. The largest boulders observed were exposed in the gorge of the Cuyon, and at that place boulders a foot and larger were very common. Most of the pebbles and boulders are very well rounded. The torrential bedding of the finer materials and the orientation of the rounded boulders indicate stream control at the time of deposition. The pebbles are mostly andesites or porphyritic augite andesites. The dikes and sills which cut through this conglomerate are of a coarser nature than the pebbles and some of them are of quite different composition.

The matrix for the pebbles is of two types. One type is water-sorted sandy material derived from tuffs or massive igneous rocks. Under the microscope this matrix proves to be composed of angular, sorted, and laminated grains chiefly of feldspar. These are bound together by secondary products in the following proportions:

	Per cent
Carbonaceous matter	5
Calcite	20
Chlorite	20

In part, however, the matrix is igneous, as in the case of a locality east of Barros where there are many conglomerate beds, some of which have an undoubted igneous matrix, and again southwest of Aibonito, especially in K. 86, where the conglomerates have an igneous matrix, and still again at the Cuyon gorge and westward along the Cuyon. The best exhibition of the igneous matrix is seen along the Rio de Cuyon, where for more than a mile the stream bed is formed by the water-polished surface of a conglomerate with a green andesitic cementing material. Structural features, such as bedding of the conglomerate, were not disturbed by the invasion of the igneous matrix, which must have entered the conglomerate in the form of an extremely fluid magma (Fig. 9).

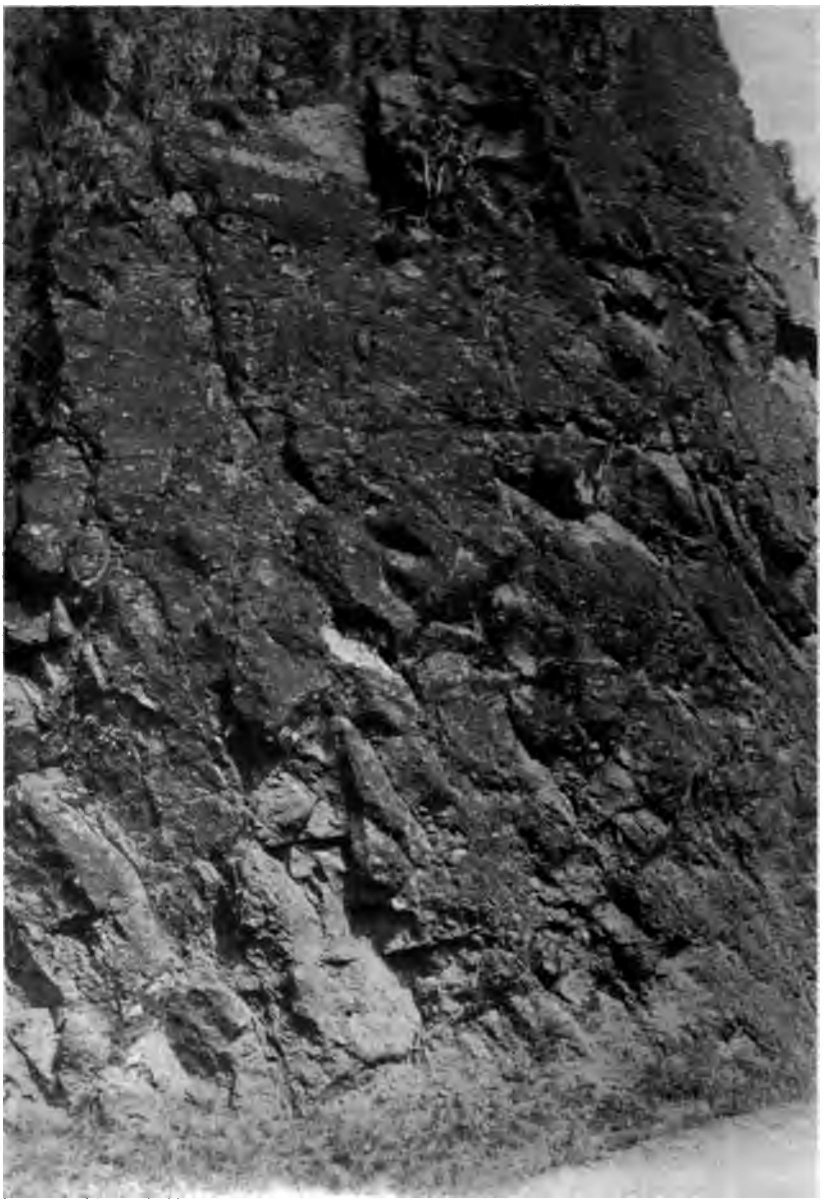


FIG. 9.—*Conglomerate with an igneous matrix*
Photographed by Professor Charles P. Berkey.

Study of the microscopic character of the igneous matrix shows it to be a massive rock of hiatal fabric. The oligoclase phenocrysts are turbid and lath-shaped, averaging from 8 mm. to 14 mm. and comprise over 40 per cent of the rock. Tabular, almost equant, pale green, and exceedingly fresh augites frequently occur as chadocrysts in the feldspar; and magnetite occurs in skeletal grains. The minerals of the groundmass are all less than .01 mm. in size and frequently they are all altered to chlorite; when not replaced they are oligoclase and augite.

Dr. Charles P. Berkey (1915, p. 23), speaking of these conglomerates as seen by him on the Military Road, southwest of Aibonito, says:

> There must be a total thickness of strata, including shales and interbedded tuffs with occasional small limestones, of perhaps several thousand feet. In all parts of the formation where conglomerate is developed, the pebbles represent the same kind of rocks as were encountered in the tuffs and intrusive masses. Actual representatives of previously solidified bedded material or indurated ash and shales are very rare, but in one case at least a pebble was observed that was judged to represent a fragment from an older silicified tuff. As a matter of fact, the materials are practically all of simple igneous character and the matrix in most parts of the formation is very abundant, or even predominant, the particles of which are of the same igneous material. The distribution of material and the range of composition leads one to believe that this conglomerate represents a special state or condition whereby materials of essentially tuffaceous origin were, immediately after their volcanic eruption, worn, rounded, somewhat assorted and bedded and mixed with related material. The fact that the conglomerate beds, which follow to great thickness, are prevailingly of simple structural habit, as compared with the calcareous shales, ash and tuff series immediately below, suggests that there may be a break here of larger consequence than is observed in other parts of the pre-Tertiary or older series.
>
> The development of so extensive a series of conglomerates doubtless does represent a considerable change in physical conditions, compared to those controlling the simpler deposits which preceded and followed them.

PHYSIOGRAPHIC EFFECTS

The conglomerates of the Sierra de Cayey play an important part in the formation of the Sierra de Cayey Mountains. Where the conglomerate beds are most numerous the mountains are higher and in straighter lines, and where the conglomerates are replaced by tuffs the mountains become less definite and more scattered as, for instance, in the eastern portions of this district. The Sierra de Cayey Range may be due to several causes, such as the erosion back of a tilted fault block, but its present relief is no doubt due to the resistance of the conglomerate. Streams which cut across the series do so at right angles and with narrow cañons such as those of the Cuyon and Jajome. The roads which pass over the mountains choose abandoned cañons or wind-gaps.

GENESIS

Because of the presence of heavy beds of rounded boulders, the origin of the Sierra de Cayey series is thought to be due to the rapid erosion of uplifted mountains and to the deposition upon their flanks of great alluvial fans. The materials of this group were not necessarily derived from the beds immediately below, because the strata beneath are not deeply eroded. Their site of deposition may have been a slope of small grade and they may have been deposited after transportation from loci of erosion a great many miles to the northward. While they were being accumulated it is possible that volcanoes were active a short distance to the east and threw out great quantities of tuffaceous rock. Under such conditions the strata on the east would have been predominately tuffaceous, and this view is supported by the fact that the tuffs, in the earlier portion of the series, contain a great number of associated volcanic flows.

The boulders found in the Sierra de Cayey series were, no doubt, formed in streams with gradients no steeper than those of the streams in Porto Rico at the present time. In the bed of the Salinas, for example, large boulders are to be found today. The fact that these boulders are found just north of Salinas, and far from their source, indicates the enormous transporting power of small streams, if favored by occasional torrents. These boulders could not have been formed by wave attack because the waves of an advancing sea will grind into silt any boulders broken off unless they happen to fall into deep water and beyond surf action. Other features which argue against a marine origin are the great petrographic variety, the discontinuity along the strike of the beds, the absence of marine fossils, and the absence of a marine succession characteristic of an overlap.

GUAYAMA SERIES

GENERAL STATEMENT

Lying above the Sierra de Cayey series is the Guayama series, the strata of which are named after the City of Guayama, located upon them in the southeastern corner of the district. The average distance across their outcrop is about four miles. The series is the most complex of all those studied in this district, for it consists of shales, limestones, conglomerates, sandstones, tuffs, volcanic breccia, agglomerates and cherts. Of these, shales are by far the most important. Lenses of limestones are numerous and there are distinct and separate beds of conglomerate.

In the western part of the Coamo-Guayama district the strata apparently all dip southward between 30° to 40°. To the east a syncline is formed between K. 24.5 and Guayama. The lower contact is gradational with the Sierra de Cayey series. If an unconformity exists between the Guayama series and the Rio Jueyes above, it was not observed in the limited time devoted to this study. Moreover, it cannot be said that the rocks differ as radically from the overlying group as do the other series. The total thickness is about 2500 feet.

SHALES

The shales constitute about 75 per cent of the rock in the group, but their continuity is broken near the middle of the group by numerous large lenses of conglomerates. Many of the shales are limy and in places they pass over into true limestones, a condition which is particularly true near the top of the group and a short distance above the bottom of the group. In the western portion of the district shales replace both conglomerates and limestones. In the central part they have the least development and toward Guayama they are replaced, in part, by tuffs. The physical character and mineralogical composition of these shales is varied. For the most part they show excellent closely spaced bedding. Where the bedding is best developed fracture cleavage is also shown best and causes them to break up into small two-inch rhomboid blocks. The color varies from very dark to light gray. These shales were water-sorted and deposited under water, as is shown by their streaked appearance, which is brought out in a decided manner upon weathered surfaces. All of the material composing these shales is volcanic and it is common to find every graduation between massive tuffs and bedded shales. Hence most of the shales should, perhaps, be called finely bedded ashes. The true character of these shales is best shown by their microstructure. The fragments range between .05 mm. and .01 mm., and occasionally larger angular fragments, of clear undecomposed oligoclase or andesine feldspar without orientation, occur which look as if they had been dropped into soft silts after having been carried by the wind. Some of the larger fragments are rounded. Feldspathic material constitutes 60 per cent, carbonaceous material 20 per cent, secondary chlorite and calcite, derived in part from the feldspars and in some shales in part from organic material, make up the remaining 20 per cent, and some secondary chalcedony is present at times.

A few of these rocks contain spherical voids arranged in lines parallel to the bedding, some of which contain *Orbitolites* sp. (?) (Fig. 10), but which, for the most part, are filled with secondary chlorite and calcite. Some of these shales, especially near the top of this series, are hard and dense, due in part to the baking influence of intrusions and in part due to introduced silica and epidote, but which in larger part is due to reorganization of organic siliceous remains.

CHERTS

The cherts are of varied colors, a condition which is dependent upon their genesis. For instance, those due to baking or reorganization are gray in color like the softer shales, and those which contain much introduced material are either a blood red or dull green. Under the microscope the genesis of the red and green cherts show that at first the ordinary tuffaceous shale was impregnated by epidote giving rise to the green chert, and later some of these green cherts were fractured and specular hematite was introduced as veins which, in part or entirely, replaced the rock forming the red cherts. Subsequently both green and red cherts have been veined with white quartz.

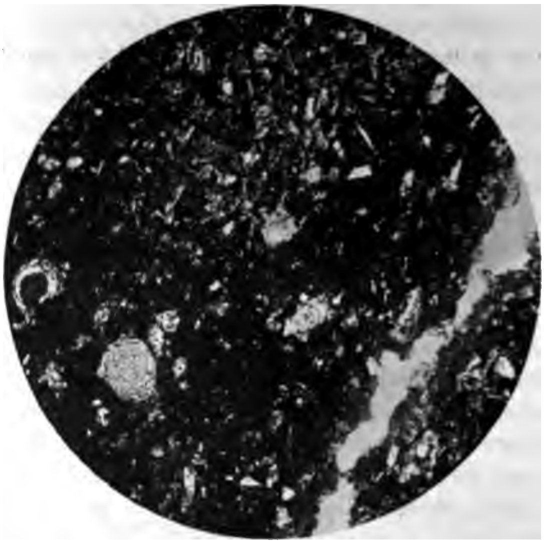


FIG. 10.—*Ash shales containing Orbitolites*

The reorganized chert shows traces of the original shale, which is composed chiefly of feldspar with streaks of carbonaceous matter bound together by secondary chlorite and calcite. Tiny spherical holes arranged in lines parallel to the bedding are numerous, some of which contain calcite, others chalcedony, and in still others the two minerals are intergrown. The occurrence of calcite and quartz intergrown indicates a contemporaneous deposition, which is chemically possible, since both are soluble in an alkaline solution. Fortunately not all of these areas are filled with reorganized minerals, but a few are filled with siliceous radiolaria or calcareous foraminiferal remains, some of which show only partial reorganization. This appears to indicate that the silicification is due to the migration of silica from reorganized radiolaria. These rocks also show micro-desiccation fractures, some of which are cemented by migrated chalcedony (Fig. 11).

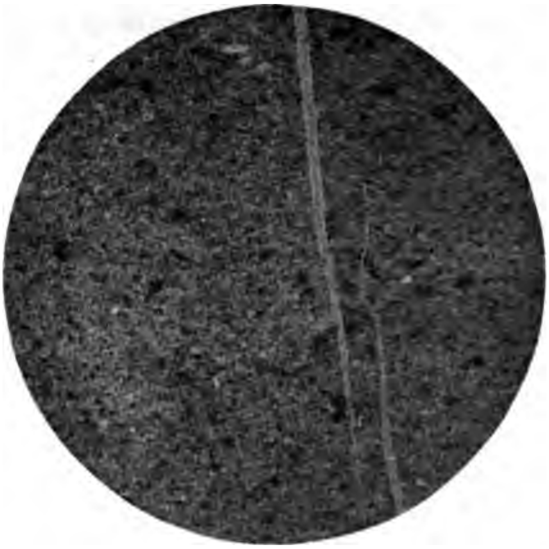


FIG. 11.—*Chert with desiccation fractures*

TUFFS

Although the tuffs occur largely in the eastern exposure of this group, yet thin beds frequently occur among the shales, limestones, and conglomerate formations. This is to be expected in view of the fact that the shales are only reworked phases of a tuff series. The presence of the tuffs with the limestones indicates the periodic recurrence of intense volcanic activities. Purely pyroclastic types cannot be sharply divided into crystal and lithic tuffs, because the two types usually occur together. Lithic character, however, is the most common in which the rock fragments are all andesitic and extremely angular and show as many as ten textural varieties of rock in a single thin section. The fragments are bound together by secondary chlorite, hematite and calcite. The production of secondary calcite in many of these clastic rocks has proceeded to such an extent that they are commonly mistaken in the field for limestones.

The crystal tuffs are composed of about 40 per cent of highly altered plagioclase fragments, areas of palagonite frequently amounting to 5 per cent, and 55 per cent of secondary calcite (Fig. 12). The tuffs weather down to a red clayey soil from which all the calcite has been leached and in which no bedded structure is apparent. Spheroidal exfoliation is rather characteristic, not only of the tuffs in this group, but of all tuffs in the island. The Hoodoo structure, which frequently occurs, results from the sticky, compact nature of the tuff soil and from the presence of small rock fragments, which serve as protecting caps to the soil below them and prevent the vertically falling tropical rains from eroding away the underlying tuff soil. The result is a multitude of pinnacles three to six inches high covering the whole face of an exposed tuff formation. The formation of the Hoodoo structure is due in part to the same factor which develops the knife-edge ridges—that is, to the compact, sticky, difficultly eroded nature of the soil.

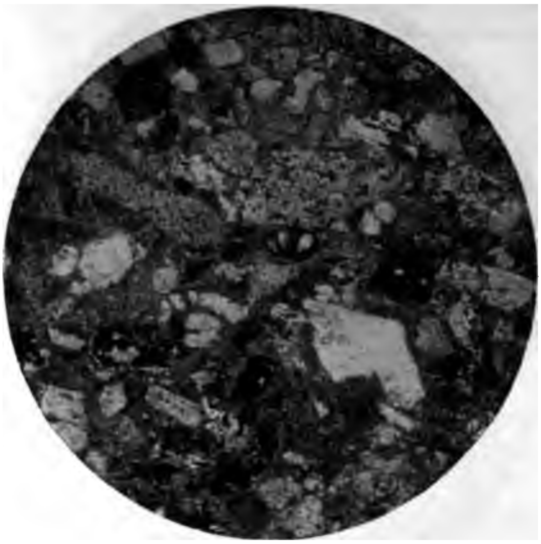


FIG. 12.—*Crystal tuff*

Not all of the tuffs are massive; some are faintly bedded. The latter are in some types composed of rather coarse, 7 to 10 mm. equigranular, rounded lithic fragments, which are usually oxidized upon the periphery.

Such fragments indicate a period of water sorting and rounding, followed by a period of oxidation. The cementing material is introduced calcite. Corresponding to the lithic is a crystal type, which is composed of rounded feldspar grains with associated carbonaceous streaks and a cement of secondary calcite, chlorite and quartz. Such characters indicate a water sorted and rounded rock. Other varieties of the bedded tuffs are composed of extremely angular grains, which are sufficiently well sorted and oriented to produce a bedded structure. The bedded structure is probably due to wind, because moving air within the limits of the size of the fragments which it can carry is more sensitive to differences of specific gravity than water, and, in addition, wind possesses a greater range of velocity. Moreover, a grain is always subject to resorting by the wind until it is finally dropped into a body of water. Most crystal tuff fragments are elongated; hence, when a tuff fragment falls to ground, if perchance it strikes upon one end, the fragment will fall over and lie upon a prismatic face. The accumulation of tuff grains all lying upon prismatic faces will result in orientation of the constituents and a development of obscure bedding structure. The essential components of all the lithic tuffs are oligoclase-andesine feldspars (40 to 50 per cent) highly altered to calcite and chlorite; also clear, fresh, fractured, equant, pale green augites about 5 per cent, magnetite 5 per cent and a few lithic fragments. The secondary cement consists of calcite and chlorite 20 per cent.

Still another variety is formed from tuff fragments which fell in the sea and became incorporated in the accumulating organic remains, such as foraminifera. Among the organic remains occur from 10 to 30 per cent of crystal or tuff fragments, some of which are rounded and evidently water-carried and others are angular and must have been windborne, but in all specimens a few well rounded grains testify to the accumulation of the organic fragments close to the littoral zone.

LIMESTONES

Akin to both the tuffs and the shales are the limestone lenses, which are, as a rule, only a few feet thick, although a few exceed 100 feet in thickness. Since they extend along their strike rarely more than a mile, the geologist is constantly bewildered by the abruptness with which they pinch out. Most of the limestones are found near the top of the group, in the central part of the district, which may indicate a former embayment of the sea. In color they are light to dark gray and in texture fine grained, and the thin sections show that these limestones are composed of clastic organic fragments, chief of which are foraminifera.

CONGLOMERATES

The best development of a conglomerate occurs near the middle of the group in the central part of the district, though isolated conglomerate beds are found frequently in other parts of this group, as near K. 99 and K. 94 on the Military Road. The pebbles and boulders are usually subangular, though some well rounded ones are to be found. Very large boulders, three feet in diameter, were seen north of Santiago. The boulders are chiefly andesitic igneous rocks with rare limestone fragments. These conglomerates in part have an igneous matrix, as, for example, those near K. 99 on the Military Road and of some north of Santiago.

AGGLOMERATES

A few beds of agglomerate occur in the tuff.

PHYSIOGRAPHIC EFFECT

In detail these rocks are affected by erosion in quite a variable manner, but considered as a whole they are carved into great spurs which extend southwestward and southward from the main axis of the Sierra de Cayey. The Military Road from Coamo to Aibonito after crossing the Cuyon River near K. 93 follows one of these spurs up to the Aibonito Wind Gap or Pass; the road from Guayama to Cayey follows another of these spurs to the crest of the range. In the great lower valley of the Salinas River there are many ridges oriented with the structure, such as Monte Sabater, west of Coqui. South of the Guamani Canal, extending from the Salinas Valley to Guayama, is a group of hills 200 to 300 feet high, developed upon resistant strata belonging to the Guayama series.

GENESIS

The origin of the Guayama series is doubtless similar to that of the Sierra de Cayey. The rocks of this series may simply be the peripheral portion of the Sierra de Cayey alluvial fans. Another and more probable view is to consider the Guayama series as the reworked portions of the Sierra de Cayey fan. After the first impulse of rejuvenation in the Sierra de Cayey had spent itself, erosion of a moderate character developed upon a lower grade. Rocks of varied types developed synchronously, because many agencies were at work. While rivers were building up a conglomerate inland and delta deposits seaward, volcanoes were active, spreading far and wide pyroclastic material, and here and there lava was flowing down a mountain side. Repeated periods of intense volcanism followed by long periods of gentle volcanic activity developed heavy beds of tuff and agglomerate and added to all the other formations some ejected volcanic material. During the dry season tuffs, perhaps gathered in the stream beds, cut into the various alluvial fans in sufficient quantities to divert the streams from their original beds in the times of flood. These periodic diversions would have started great mud-flows down the mountain sides, causing pebbles and boulders to be swept along with the mud-flows, all becoming more or less rounded *en route.*

Periodic encroachments of the sea gave rise to marine lenses. To do this a very slight subsidence would have been sufficient because (1) the delta phase of the piedmont plain would not have extended much beyond the shore zone and (2) in tropical regions, as shown in Porto Rico at the present time, limestones are laid down not only in the neritic zone, but commonly in the zone between high and low tides, and also some are formed beyond the reach of the sea, such as deposits of tepetate.

Rio Jueyes Series

GENERAL CHARACTER

The Rio Jueyes series is named from the river which flows over their central exposures. The series extends in a broad belt with an outcrop 4 to 5 miles broad and reaches from the west central part of this area southeastward, passing beneath the sea south of Guayama. Its one outstanding difference from the Guayama series is the number of limestones contained within it. The limestones, however, do not exceed in volume or number the shales, tuffs, or conglomerate beds. Lenses of agglomerates and volcanic breccias are numerous.

STRUCTURE

The rocks of this series differ from adjacent series sufficiently to make them worthy of a separate grouping. Their upper contact is sharp and clean. In fact, in many places the point of the geological pick may be placed where the Rio Jueyes series ceases and the Coamo Springs limestone series begins. The beds generally dip S. 30°. The total thickness may be as much as 5000 feet.

LIMESTONES

Two types of limestones occur, the white algal limestones and the dark gray crystalline, fine grained, highly bedded limestones.

Limestones begin to occur in the lowest formations and in Santa Sabater Hill reach their best development. This is a long, narrow, homoclinal hill north of Central Aguirre, which rises as a mendip, or morro, through the thin coastal plain deposit. The limestone beds composing this hill are in themselves variable; some have a cream tinge, are porous, and have an evident organic structure; other beds are highly crystalline, fractured and cemented by white calcite. Interbedded with both limestones are thin beds of tuffs. Both develop a pitted and cavernous surface upon weathering. It is remarkable how this limestone, soft and porous as it is, stands up as a resistant ridge. Everywhere in Porto Rico the limestones are resistant to weathering. Some form great ridges like the Coamo Springs limestone described below, others remain only as gentle swells, but everywhere they rise above the shale or tuff beds.

In thin section the white limestones are seen to be made up largely of honey yellow or colorless crystalline calcite. Rounded outlines, but without identifiable structures, indicate the former presence of organic substances such as algæ, which are present in tiny fragments, and foraminifera, such as *Globigerina cretacea, Globigerina bulloides* and *Truncatulina lobatala,* all of which indicate a very early Tertiary age.

Other limestones are fine grained, showing light and dark shades of gray and buff, and occur as thin, discontinuous lenses. Some may be 100 feet thick, but all those whose thickness could be determined are only a few feet thick. Most of the lenses are found in the eastern half of that portion of this group which rises above the recent coastal plain deposits. One rather continuous series of lenses, traced from southwest of Guayama across the district, occurs south of La Lapa, south of Santiago on the Rio Jueyes, south of Coamo on the Coamo River and again on the Descalabrados River. The lenses always occur among the shales into which they grade. Megoscopic volcanic material is present in many of them.

Under the microscope they are seen to vary from a tuffaceous limestone to a tuff with many shells. The organic fragments are comminuted pelecypod and gastropod shells with numerous foraminiferal remains, and diatoms, such as *Miliolina seminulum* Linné? The foraminifera observed are:

Orbulina universa?
Orbitoides papracea (Boubee).
Textularia gibbosa, d'Orbigny.
Globigerina, d'Orbigny.
Numulites sp.?
Gaudryina sp.?
Polymorphina sp.?
Miliolina sp.?
Biloculina sp.?

The rodiolarians are chiefly *Porodiscus concentricus*. The organic remains have all been more or less recrystallized and no calcareous algal structure was noted. The tuffaceous material is usually very highly altered feldspar laths with occasional lithic fragments. The feldspars and lithic fragments alter to calcite and chlorite.

SHALES

The shales, like the limestones, are best developed just west of the Salinas River, where they are finely bedded, siliceous and occur as frequent layers among the argillaceous phases. The color varies from buff to gray. In thin section they are seen to be made up of a streaked dense material, chiefly quartz and some carbonaceous material. Little spherical holes, which are arranged in lines parallel to the bedding, make up about 1 per cent of the rock. Most of the tiny cavities are vacant, a few have a calcite filling and an occasional one has a diatom or radiolarian in it, such as *Melospira arenaria,* Rab., and *Coscenodiscus marginarus,* and similar types.

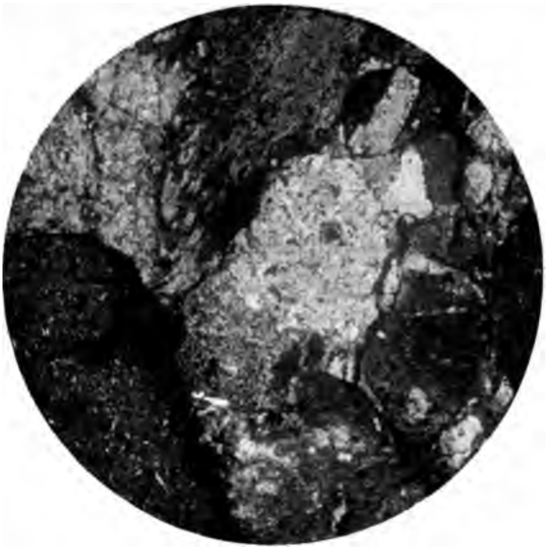


FIG. 13.—*Lithic tuff*

TUFFS

Beds of tuffs are exceedingly common. Beds of limestone are often sharply divided by a thin layer of tuff; most of the conglomerates have a tuffaceous matrix and some of the shales grade into tuffs. The pyroclastic formations are best developed in the western portion of the group. As in the older group, the tuffs may be divided into the lithic and the crystal groups. The lithic tuffs are frequently very beautiful rocks, since they are composed of angular fine-grained rock fragments of extremely varied colors, such as black, red, green, brown and purple. An excellent exposure of this type is found in the stream bed east of Coamo. The rock types present in the lithic tuffs are always andesites and as many as ten different varieties based upon texture may be present in one thin section. The fragments are cemented by calcite and chlorite and some are well bedded (Fig. 13).

The crystal tuffs do not differ from those described in the older series. They consist of lath-shaped altered oligoclase andesine feldspars, clear, fresh, pale green, embayed and fractured augites and grains of magnetite, all cemented by secondary calcite, chlorite, limonite and some zoisite. These secondary products are all derived from the feldspar and a former volcanic dust matrix.

CONGLOMERATES AND AGGLOMERATES

In the Rio Jueyes series frequent beds of conglomerate and agglomerate occur. The beds are never thick nor continuous along the strike and as a rule they are formed of well rounded pebbles and boulders of andesite and andesite porphyry. An interesting formation occurs about two miles north of the Rio Jueyes Water Gap, which consists of numerous well rounded three-inch pebbles of limestone, dark gray in color and highly fractured, with the fractures cemented by calcite. Among the well rounded pebbles also occur frequent three to six inch angular agglomerates, all in a tuffaceous matrix. Beds of this conglomerate six feet thick alternate with two-foot beds of shale. Two factors alternated to produce this formation: near-by volcanic eruptions, which gave rise to the tuffs and agglomerates, and stream erosion, which produced the conglomerates. The great falls of volcanic debris, probably diverted to streams first from one side of the alluvial slope down which they were flowing, and then to the other, and in this way the alternating beds of shale, conglomerate and agglomerate were produced.

PHYSIOGRAPHIC EFFECT

In part the Rio Jueyes series partakes in the formation of the spurs extending from the south flank of the Sierra de Cayey, and in part assists in the formation of an independent landmass south of the Rio Cuyon and west of Salinas. A series of great subsequent valleys is carved out of the southern half of the western third of the Rio Jueyes rocks. The eastern half of the series lies beneath the Santa Isabel coastal plain deposits and, therefore, exposures are to be found at only infrequent intervals.

GENESIS

From the facts stated above it appears that the conditions of accumulation were much the same as in the previous period. Mountains composed of older strata were being dissected and out of them alluvial fans of deposition were formed. Those portions of the fans which dip into the Caribbean Sea gave rise to shales, while conglomerates were formed in the ever-shifting stream beds. Between the projecting prongs of the fan the embayed sea was the site of calcareous deposition, and so limestones accumulated at stratigraphic horizons equivalent to the shales. Volcanic vents, of which a large number have been found in this district, gave forth moderate amounts of tuff continuously and at times exceptionally large quantities of both tuff and agglomerate. The result was that a series made up of alluvial fans alternating with local lenses of marine limestone was formed.

Coamo Springs Limestone Series

This series is named from a thermal spring located in the Coamo River Water Gap. It extends as a homoclinal mountain from Central Aguirre northwestward to the Descalabrados River and thence to the Jacaguas Reservoir. The Central Aguirre Hills are thought to be part of the same formation, a conclusion based upon the close similarity of the rocks and the alignment of these hills with the general trend of the Coamo Springs Range. If these hills are formed from the Coamo Springs limestone, then this formation continues eastward beneath the Caribbean Sea. The total length is at least thirty miles and the thickness about 800 feet. This group is composed essentially of a single formation, a heavy bedded, steeply dipping limestone, which forms one of the most interesting petrographic types and erosional features in Porto Rico. In addition to limestone, however, there are many thin beds of tuff within the limestone, into which the limestone grades at its top and bottom. Near the top and bottom the tuff beds get thicker and more numerous until the limestone ceases entirely.

STRUCTURE

The limestones and associated tuff beds of the Coamo Springs group have been tilted to rather high angles and in places faulted. In the

Aguirre Hills the dip is 45° S., at Salinas Hill 45° S. and at Jueyes Water Gap there is a change in dip from the top, where it is 70° S., to the bottom, where it is 45° S., which indicates the south limb of an anticline. West of the Coamo River the dip varies between 35° S. and 50° S. and in the vicinity of the Rio Descalabrados anticlinal structure is well shown (Fig. 14). The good evidence of anticlinal structure to the east and west of the Coamo River Water Gap suggests that the structure at the gap is also anticlinal, even though it is not evident there because of the massive character of the rocks. An anticlinal structure at this point would explain the great breadth of exposure of the limestone.

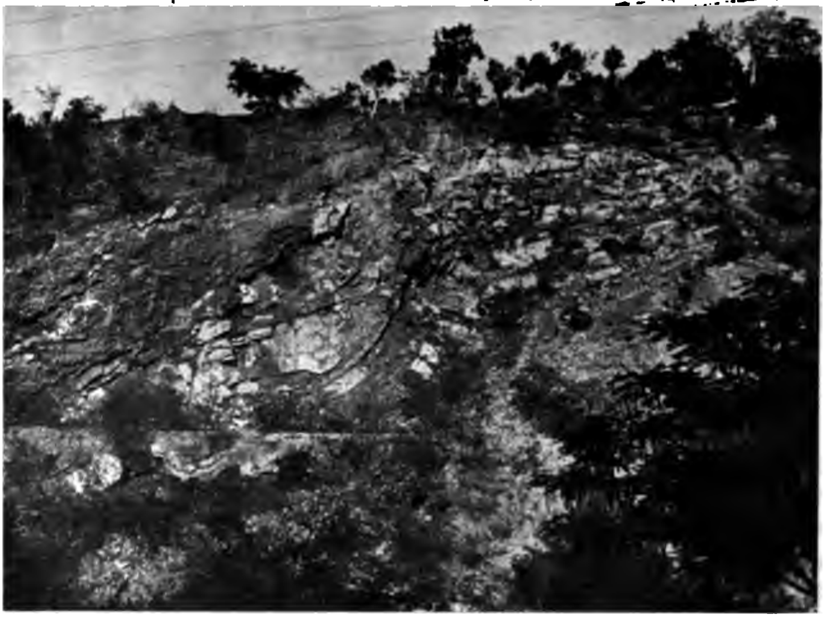


FIG. 14.—*Coamo Springs limestone exposed in the Descalabrados Gap*
Photographed by Professor H. E. Crampton.

The whole range is arranged *en echelon*. The continuation on the westward side of the Rio de Coamo is almost a mile south of a line continued from the Cerro Pimentol westward, and in like manner the Cerro Gavia is broken in two places. These are features explainable only by faulting. The contacts of the Coamo Springs limestone series are the best marked of any rocks in the district.

LIMESTONE

The appearance of the limestone which forms this series is variable, yet certain features are so constant that the rock may be recognized at a glance and can be easily distinguished from all other limestones occurring in Porto Rico. The color varies from chalk white to cream or to pale lilac. The grain is very fine in most occurrences, but in part it is medium, and the size of the grain increases to the westward. Some of the rock is made up wholly of crystalline limestone, but for the most part it is mottled with organic and tuff fragments which are brown, soft and may easily be picked out with the point of a knife. The organic fragments vary in size from 1 to 3 mm. and are cream-colored. Their organic character is apparent even in hand specimens, as shown by concentric zones in which a fine mesh structure can be seen. Other varieties have a fine-grained lilac-colored material stained with hematite, forming a matrix for the organic bodies. The thalli of the algæ of which this rock is largely composed are shown in figures 15, 16 and 18.

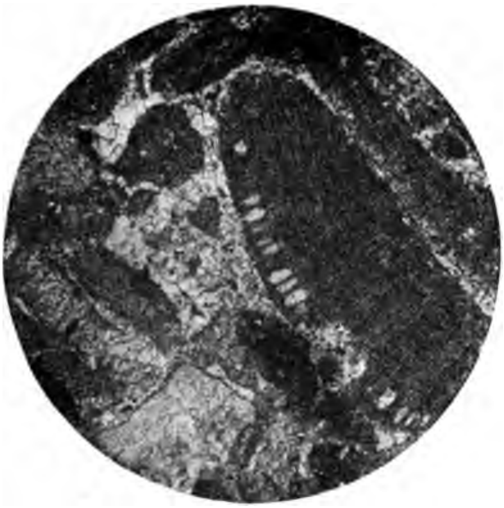


FIG. 15.—*Lithothamnion thallus in cross-section in the Coamo Springs limestone*

The microscopic character of this rock is most interesting. It is found to consist of at least three varieties of algæ-like structure. Some of these are undoubtedly of the red calcareous algæ type. Figure 16 shows one form that has a fucoid appearance, which is apparently the spore case of a thallus in longitudinal section, and 15 a thallus in cross-section. In addition to the algæ structure, foraminifera of several species are present, some of which are *Amphistegina* sp. (Fig. 19), *Discorbina globularis*, d'Orbigny, *Orbitoides* sp., *Globigerina* sp. (Fig. 42); ostracoids also occur, all of which testify to a Tertiary age. The interstitial substance is made up of interlocking calcite grains averaging .05 mm. in diameter, which have evidently been derived from the organic bodies (especially the algæ) by recrystallization. This is shown by the transition contact between the two and by the shadowy outlines of thalli in crystallized calcite. The organic structures have been highly fractured, broken and cemented by limonite before the induration of the rock took place. This suggests dry-land conditions. The tuffaceous matter consists of fractured crystals of the oligocene-andesine varieties. Chlorite areas are also present, suggesting former pyroclastic grains. In some a bright green glauconitic-like substance occurs.

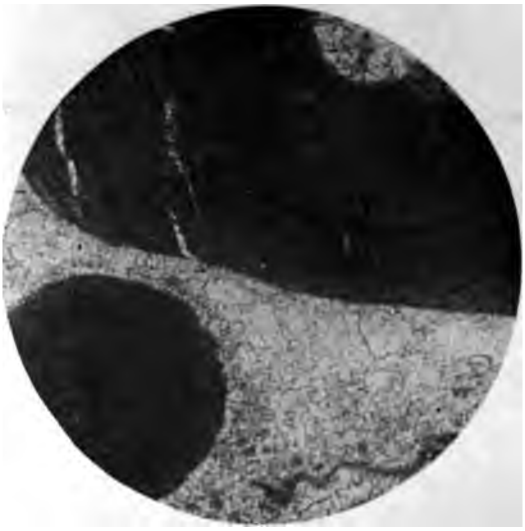


FIG. 16.—*Lithothamnion thallus in longitudinal section in Coamo Springs limestone*

TUFFS

The tuffs have no features different from those described above.

PHYSIOGRAPHIC EFFECT

Because limestones are not eroded with ease in the tropics, the Coamo Springs limestone stands up as a ridge of southward-dipping rock.

Aguirre Hills are only a few hundred feet high (Fig. 17) and are separated from the rest of this homoclinal mountain by the broad valley of the Salinas River. Salinas Hill, the eastern extremity of the Cerro Raspado, rises to four hundred feet, and from this place the elevation increases till just east of Coamo Springs, where the elevation of the Cerro Pimentol is one thousand feet. Just west of Coamo Springs the elevation is again only six hundred feet, but it rises westward to over one thousand feet at Jacaquas Reservoir. To the north a great subsequent lowland has been carved, and to the south and east of the Coamo River the coastal terraces, carved in a later formation, reach to the foot of these mountains. Wind-gaps in its crest are common. In places the crest is double and in others triple, due to the intercalated and easily eroded beds of tuff.

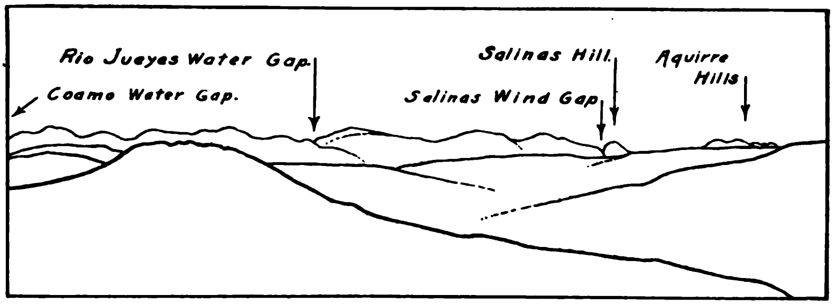

Rio Jueyes Water Gap.
Coamo Water Gap.
Salinas Hill.
Salinas Wind Gap
Aquirre Hills

FIG. 17.—*Coamo Springs Range*

The sky-line is formed by the crest of the Coamo Springs Range. The middle portion of the sketch is occupied by the present coastal plain.

GENESIS

Specimens selected either at random or by intent from various portions of the limestone formation universally show algal structure. In some parts, where only little shreds and fragments are to be found, the former presence of algæ is attested to by the faint outlines of their former thalli preserved in the recrystallized calcite. From top to bottom and throughout the entire length the formation was originally composed of about 40 per cent algæ—an estimation based upon the percentage found in the many thin sections studied. In some of the thin sections and hand specimens the ramifying branches of the former plants can still be seen, but for the most part the algæ are in fragments. The fragments are more or less rounded and, of course, this rounding is largely the result of surf-work, but in part it undoubtedly was due to terrestrial agencies—wind and flowing water—as shown by the oxidized borders of many of the worn algæ fragments. Some of the oxidized and other fragments possess fractures which, cemented by calcite, must have been formed at a time previous to the development of the matrix. Among the algal structures are frequent tests of foraminifera; these have such an intimate relationship with the algæ that there is no doubt about their synchronous accumulation. After the algæ debris with the associated foraminifera had accumulated, static metamorphism at the time of accumulation, and perhaps dynamic metamorphism after accumulation, recrystallized the interstitial algæ and foraminiferal silt to form a matrix. This recrystallization did not cease with a conversion of the lime magnesia silt, but continued to reorganize the more perfect organic structures until in part these were almost obliterated.

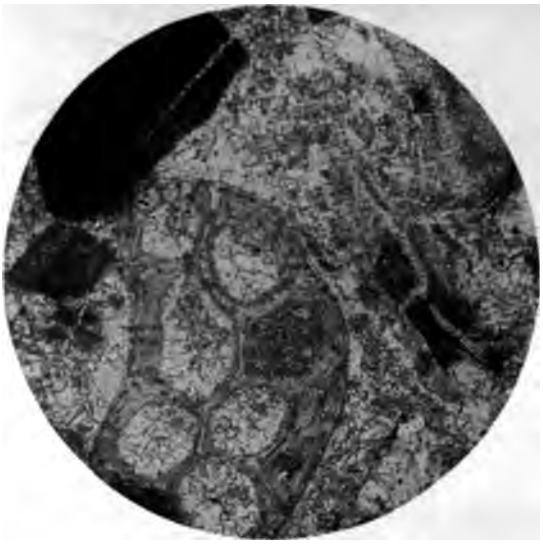


FIG. 18.—*Lithothamnion in Coamo Springs limestone*

The above discusses the data derived from the rocks themselves. Information from other sources will give us a clear idea as to the lithogenesis of this formation. In the first place it is evident that algæ cannot live below a bathymetric zone penetrated by sunlight. Observations the world over show that algæ are lovers of the zone exposed between high and low tide and of the neritic zone which extends down to 200 meters.

Foslie (1907) states that "the reefs of Chagos are covered by an enormous quantity of nullipores (*Lithothamnia*, etc.) incrusting, massive, mammillated, columnar and branching. The outgrowing portions of the reef are practically covered by their growth"; and Howe (1912) says: "The massive beds of *Halimeda opuntia* off the Florida Keys (the same species, by the way, that is filling the lagoons of the South Sea atolls) are striking, as are the banks of *Goniolithon strictum* in the Bahamas and reefs of *Lithophyllum daedaleum* along the shores of Porto Rico. However, the lime-secreting plants appear to be much more generally and widely distributed, both horizontally and vertically, than the corals."

Also Kjellman (1883) writes that "*Lithothamnion glaciale* covers the bottom in deep layers for several miles, along the coast of Nova Scotia and Spitzbergen, at depths of about 30 meters"; and Weber (1904) that "near the coast of Haingsisi, an island near the southwest point of Timor, the *Siboga* anchored twice . . . the second time good luck favored us; it was spring tide; the water sank very low and we could observe that the whole reef . . . consisted chiefly of *Lithothamnion erubescens* f. *Haingsisana.* It was remarkable that the branching knolls remained quite dry during several hours of the day, exposed to the glare of the tropical sun, and that this seemed not to injure them. . . . This *Lithothamnion* bank struck me, because it is such an unique sight to see the ground, as far as the eye can reach, covered by the pretty, beautifully colored knolls, which are heaped up so close together that, while walking, one crushes them continually, making a peculiar noise as of broken china."

From the above facts the genesis of the Coamo Springs limestones may be deduced. In the shallow waters of the southern coast of Porto Rico unsegmented calcareous algæ grew in rank profusion. The peripheral portion of the algæ was easily broken off and ground up by the surf. Some of the algæ were exposed at low tide and their fragmental portions were picked up and carried inland by the wind. Shallow-water foraminiferal shells became entangled among the algæ. Upon the silts and debris of the comminuted algæ more algæ grew. It is not necessary to postulate a subsidence. When the surface of the silts due to their accumulation reached too shallow water for neritic forms to exist, their places were taken by those which preferred daily exposure to the tropical sun, and *pari passu* with this the neritic types moved outward. Wind continued to carry exposed and dried algal dust and fragments inland to accumulate upon the dry land. By such a process an indefinite thickness could have been developed. In the case of the Coamo Springs limestone, conditions favorable to algæ growth lasted long enough for the development of a formation about three to eight hundred feet thick.

ORIGIN OF THE DOLOMITES

To the writer it seems that there can be no doubt about the shallow-water origin in the main and the terrestrial origin in part of this limestone. If this is the case, then a safe deduction is that the species of foraminifera occurring associated with it are also of shallow-water origin, or that foraminifera can be drifted shoreward and accumulated under shallow-water conditions. Since the foraminifera in the Coamo Springs limestone are identical or similar with those found in older and younger limestones, not containing algæ remains, it is probably safe to conclude that these limestones, too, were formed in shallow embayments of the southern coast. To accept this view assists in the explanation of the occurrence, character and relationship of the limestone lenses.

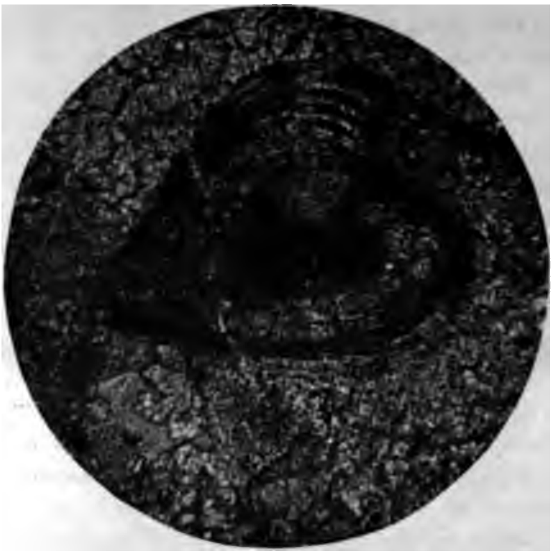


FIG. 19.—*Amphistegina in Coamo Springs limestone*

Calcareous algæ contain a great deal of magnesium carbonate. This is shown by the average of fourteen analyses (Högbom, 1894) of *Lithothamnion* selected from all parts of the world, which is calcium carbonate 80.29 per cent and magnesium carbonate 8.14 per cent.

In the processes of crystallization there may have been a residual enrichment due to the more soluble character of the calcium carbonate and a dolomitic limestone may have been formed. Algæ were undoubtedly the more dominant form of plant life in the earlier geological periods and the suggestion is offered that the dolomites of the early Paleozoic may have had their origin in this manner.

Rio Descalabrados Series

GENERAL CHARACTER

The series is named from the river which flows across them at their widest exposure. All the strata of the older series occurring above the Coamo Springs limestone belong to this series. It is largely covered by coastal plain deposits; hence outcrops are few and isolated and are found chiefly in a few road-cuts. West of the Coamo River a series of parallel hills rise through the coastal plain deposits and produce the exposures upon which this discussion is based. This group is composed of limestones, shales, cherts and tuffs.

STRUCTURE

The rocks all dip seaward at angles from 20° to 50° and the strike is uniformly N. 30°–50° W. Between the Coamo and Descalabrados Rivers the rocks are broken by a normal fault, which is thought to be the same fault that offsets the Coamo Springs limestone. The lower contact is sharply defined, but the upper contact is unknown because it lies beneath the Caribbean Sea. The thickness of this series is at least 3000 feet.

LIMESTONES

Three distinct limestones occur which resemble each other very closely in a petrographic way and which are separated from each other by thick beds of shales, cherts and tuffs. The variations which do occur are of a linear character—that is, they grade into each other from top to bottom or along the strike. The color is gray except where the limestones contain much included tuffaceous material, which gives them a green or yellow shade. The grain is medium or coarse crystalline where the rock is homogeneous, except where large quantities of tuffs are present which appear to have prevented complete recrystallization. The lowest limestone formation is the most impure and resembles the Coamo Springs limestone very much. This is especially true in that outcrop forming the hill to the east of the Coamo Springs Reservoir. All these rocks are highly fractured and cemented with calcite.

In this section these limestones are seen to be made of three types of material: organic, volcanic and recrystallized calcite. The organic material consists of algæ, which are most numerous in the bottom limestones. Foraminifera are common in all three formations, some of which are *Nummulites* sp., *Orbitoides* sp., *Biloculina* sp., *Miliolinas* sp. and *Globigerina* sp. The tuffaceous material consists of oligoclase—andesine feldspar altered to chlorite, calcite and limonite. Depending upon the abundance of one or the other of the secondary minerals, the color of the rock is olive green or a buff yellow. Grains of magnetite are common and a few pieces of devitrified palagonite occur. The binding of calcite has been developed from interstitial lime silt and from the larger organic remains. In many ways the origin of these limestones was identical with that of the Coamo Springs formation.

SHALES AND CHERTS

The shales and cherts form finely bedded deposits occurring between the limestones. Most are silicified, a few epidotized, and some are calcareous and others are argillaceous. The excellent bedding is an expression of a very fine lamination, microscopic in size which weathering brings out in relief. The colors are black, dark gray or green. Microscopically these shales and cherts are of a dense material the composition of which it is impossible to determine, but is probably a very fine secondary quartz with carbonaceous streaks, sericitic flakes and limonite bands. Most of these rocks contain small spherical holes arranged in lines, some of which cavities are filled with quartz, others with quartz and calcite and still others have radiolarian remains. As the radiolaria can be seen to alter secondary quartz, the calcite must be tertiary and

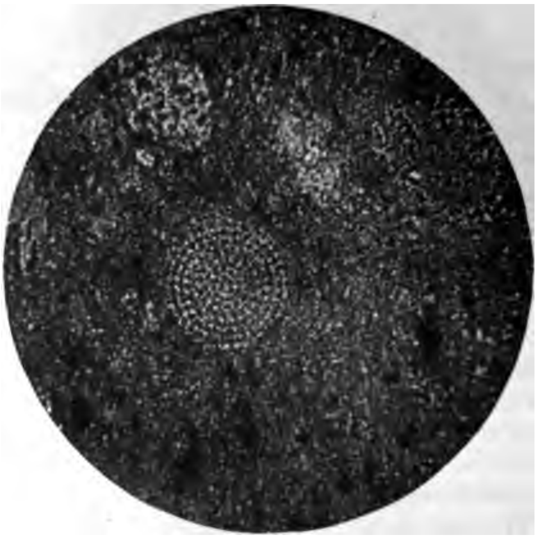


FIG. 20.—*Porodiscus concentricus in shale*

introduced, probably, under thermal conditions. Some of the shales are fractured and the fractures cemented by epidote which develops outward from the fractures and in some entirely replace the rock. The silicification is thought to be due entirely to recrystallization of the radiolaria and diatoms, some of which are *Heliodiscus humboldti* Ehr. and *Porodiscus concentricus* Ehr. (Fig. 20) and diatoms of the type of *Melosira* sp. The highly bedded character of the shales belonging to this group is shown in figure 21.

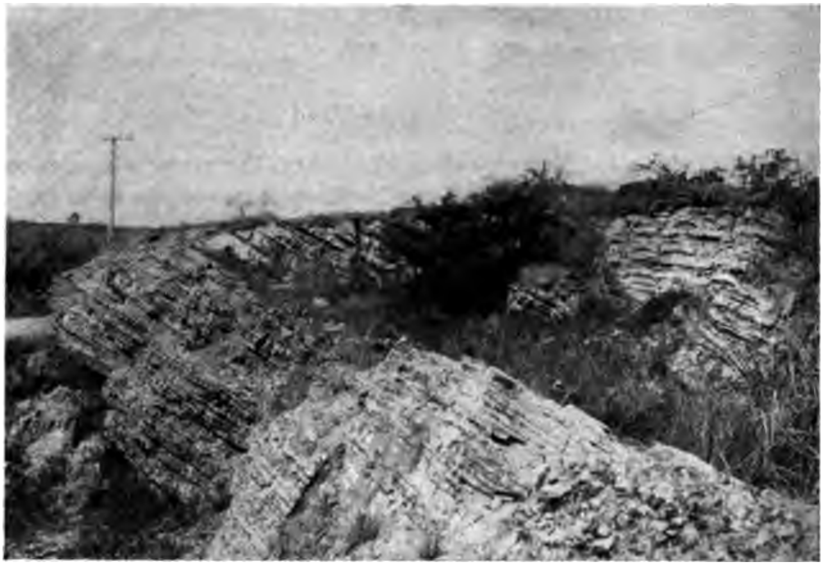


FIG. 21.—*Shales of the Rio Descalabrados series*
Photographed by Professor Charles P. Berkey.

PHYSIOGRAPHIC EFFECT

West of Central Aguirre the recent marine terrace is carved upon the upturned edges of Rio Descalabrados series. A few hills, due to the resistant limestone beds, are separated by a series of small subsequent valleys opening up toward the Coamo and the Descalabrados Rivers. These hills are divided into three parts by the Coamo and the Descalabrados. Of these the small limestone hill east of the Coamo Reservoir is the northeasternmost division. In addition to the three major divisions so formed, these hills are again divided by small resequent valleys.

GENESIS

The view is held that these shales are entirely of delta origin, which is indicated by the excellent bedding, the carbonaceous streaks and lenticular character of the beds. During the period at which this group was formed there was an intermittent subsidence, so that after delta shales had accumulated offshore limestones would develop. The subsidence was sufficiently graded so that before the limestones could reach a notable thickness a newly formed delta advanced seaward and covered them. A later subsidence gave opportunity for a new limestone deposit. This condition was repeated at least three times.

ARECIBO FORMATION

This formation has been described by Berkey, the name being derived from a river on the north coast where the limestones occur in great thickness. The Arecibo caps a hill 100 meters in diameter in the southwestern corner of the Coamo-Guayama district. This formation once covered the district over a much greater area, as is shown by the erosional border lying just west of the district, by the isolated remnant of erosion above mentioned, and by the superimposed drainage.

Because of its importance in the interpretation of the geological history of this region an extended quotation from Berkey (1915, p. 50) is perhaps admissible:

> Both on the north side, for nearly the whole length of the island, and on the south side, over the western half, there is a bordering belt of limestone and associated beds that have been developed on an eroded surface which beveled across the more complex structures of the older series of formations that formerly made up the mass of the island. These limestone beds are several hundred feet in thickness and dip gently toward the sea. On the inner margin of their present extent toward the interior they are abruptly terminated in a very irregular line of modified cliff forms facing toward the prevailing smoother and lower ground for some distance toward the interior. In its best development, however, it is a typical cuesta, formed in the usual manner by the erosion of a formation representing a recently uplifted coastal series. The series of formations involved formerly extended inland very much farther than they do now. Only the outer margin remains from the erosional construction of a series of beds and reefs that in former times covered a large portion of the island. . . .
>
> In a large way this series forms a structural unit. Below it lie the older and more complicated igneous and sedimentary rocks. The break between these two represents the chief unconformity in the whole geological column. For a considerable distance an average dip of 30° to 36° was estimated and the total thickness represented, based upon the width of the belt, must be at least 3000

> feet. As one goes eastward, a comparatively short distance they are almost entirely lacking. . . .
>
> Between Guanica and Juana Diaz, wherever the inner margin of the Arecibo formation was seen, it was bounded by a fault which brings the upper beds abruptly against the older tuffs and shales of the pre-Tertiary. The formation furnishes an abundance of fossils. The lower portion of the lower beds on the south side of the island, as seen at Juana Diaz, seem to be the most promising for a determination of the age of the beds of the formation. . . .
>
> The formation as a whole is essentially a structural unit. . . .

These rocks are separated from the older ones by a discordant unconformity or structural unconformity. This is shown by the manner in which these gently dipping Arecibo limestones rest on rocks tilted to high angles and by the fact that they rest on a peneplane surface.

The existence of this peneplane was first observed by Berkey, who says:

> Beneath the limestone constituting the cuesta and representing the Tertiary series, there are, in numerous places, traces of a former plain that represented the results of erosion on rocks that had a complex structure. Occasional profiles of more distant ridges also show a sky-line that suggests the former existence of such a plain, and in favorable localities it can be traced directly to the foot of the limestone cuesta. Occasional traces are also seen on more mountainous tracts, especially at the west end of the island, near Rincon and in the vicinity of Mayaguez. It is the judgment of the writer that these all belong to a single base-leveling surface or marine-cut platform formed in the period just preceding the development of the Tertiary limestone series.

The peneplaned surface has been elevated and tilted. The elevation is 2500 feet in the eastern portion of the Coamo-Guayama district and 3000 feet in the western. It descends toward the north. Dissection has cut down far below the level of the peneplaned surface to the south, and so its former trend can only be inferred. Were it not for dissection the former peneplaned surface would attain at least another thousand feet at the southern coast.

That the Arecibo limestone once covered the entire district is shown by the superimposed condition of the major streams. In the above paragraphs the general strike of the stratified rocks is described as northwest and southeast, but the large streams, excepting the Rio de la Plata, flow southward. It might be argued that the original drainage was parallel to the structure and that coastal streams have worked back and captured them. Such problematical coastal streams would have received their initial supply of water from the most arid portion of the island, while the captured streams were supplied by the heavy daily rains of the interior. To capture under such conditions is impossible and the theory must be abandoned. The large streams have courses discordant with the structure. This is shown in most striking fashion by the Rio Descalabrados.

Coamo and Jueyes, which pass at angles of ninety degrees and comparatively narrow water gaps through the Coamo Range.

PHYSIOGRAPHIC EFFECT

One result of the superimposition of the drainage across the structure of the rock has been a numerous series of captures. A good illustration of a recent one is cited. A channel filled with pebbles lies between Salinas Hill and the Cerro Raspado. Back of this latter range a subsequent branch of the Rio Jueyes flows, and it seems evident that this latter stream has captured the headwaters of this nameless stream and diverted them eastward. As a result a wind-gap, which is so low that a wagon road passes through it, has been formed.

SANTA ISABEL SERIES

OCCURRENCE

This formation is named from a little village situated upon the coastal plain deposit in the southwestern part of the district. Deposits of the Santa Isabel series cover the southern border, extend as embayments up all the rivers flowing across the coastal plain, and occur as isolated patches along the various rivers.

GENERAL CHARACTER

For the most part this series is composed of a fine black alluvium of varying thickness. Thus, west of La Lapa the Rio Cerro shows 20 feet of bedded silts interlarded with boulder beds. North of Salinas Hill it is 25 feet, near the Baños de Coamo the river flows between vertical silt walls 50 feet high (Fig. 23), and at Guayama the silts are only a few feet thick.

All of the alluvium found in the valleys of this district cannot be classed as a coastal plain deposit (Fig. 2). Some is due to a local base-level created by a hard rock partially damming some stream. Streams dammed in this manner have aggraded their valleys with alluvia to considerable depths. Thus, three miles north of Rio Jueyes Water Gap is a deposit 25 to 30 feet thick composed of excellently bedded silts with an occasional lens of pebbles, and in this stream there are also alluvial beds at 660 feet elevation. Again, in the great Barranquitas-Cayey subsequent lowland is a deposit of silt 10 to 15 feet thick, due to a local base-level located just south of Comerio which is about 1500 feet above sea-level. Such deposits are classed with those of coastal plain because they have been formed in Recent times.

The coastal plain rests upon the upturned edges of a series of tuffs and shales and upon these planed surfaces wave-rounded boulders are frequently found, as shown in a cut of the road southeast of Guayama. Between and on the top of the Aguirre Hills such boulders occur in profusion and represent the time when the sea was awash with the tops of these hills. Some of these perfectly rounded boulders are of Arecibo limestone which must have been transported littorally a great many miles.

In the beds of many of the streams deposits of chalky white, porous limestone are being formed. These tepetate deposits form in the shallows of the intermittent streams, where the waters evaporate rapidly. They are also formed at points where the water cataracts over a small ledge and loses some of its carbon-dioxide content and is thus forced to precipitate its heavy load of calcium carbonate.

PHYSIOGRAPHIC EFFECT

When the coastal plain was in process of creation the streams previously developed upon the old land entered the sea at the inner margin of the present coastal plain. With the retreat of the sea the rivers flowed over this coastal plain and some of the streams, like the Coamo, sought out their old courses and became resurrected, while others, like the Descalabrados and the Rio de la Lapa, were not able to cut through the coastal plain upon which they meander to the sea. These streams meander upon reaching the coastal plain because they lose much of their water through the silts and gravels. This lost water, upon reaching the surface of the wave-cut terraces, seeps along the top of these terraces to the sea. This seepage furnishes the only zone of water to which wells may be driven in the whole Coamo-Guayama district.

Still another class of streams was created for the first time upon the gently inclined surface after the emergence of the coastal plain. The lower portion of the Guamani belongs to this classification and the Rio Cemarrona is another good example which by headward erosion has begun to eat into the old land behind the coastal plain.

The superimposition by the coastal plain of some streams has caused marked changes in drainage. Thus, the present course of the Guamani is either due to capture or to the superimposition of a stream which formerly flowed down the wide-open valley east of Guayama hills, but now flows down to a point marked by arrow (Fig. 22) and then turns abruptly westward through a narrow cleft in a spur of the mountains and then flows southwestward to the sea.

The terraces found at the lower end of the Coamo, and to a less extent associated with the other streams, are due to the dissection of the embayed portions of the coastal plain. The elevation of about 250 feet which brought the coastal plain to view revived all the streams. The reviving influence of uplift took place long enough ago that the effect is now active in the headward courses of such streams as the Rio de la Lapa. In the upper reaches of the streams degradation is cutting into the old complex of volcanic rock. Figure 23 shows how the Rio de Coamo has cut a young valley 50 feet deep into the alluvium accumulated when the Coamo stood at the highest level during recent times.

Most of the streams in this district have cut laterally faster than they cut downward. This lateral cutting flattens the floor of the valley. The cut continues to one side until the streams meets a resistant rock which reflects it to the opposite side, and a deflection in a stream once started continues until deflected again. Associated with lateral cutting is downstream cutting. The combined effect is to produce a terrace. Slow uplift of streams which are provided with rocks in their banks to deflect them will cause a series of terraces to be cut one below the other. Ledges of rocks projecting into the stream are ideal for this purpose. The Rio de Coamo is deflected by the Coamo Springs limestone and as a result three terraces are formed. Continued uplift has caused these to be dissected by consequent streams into a dendritic pattern. The highest terrace of the

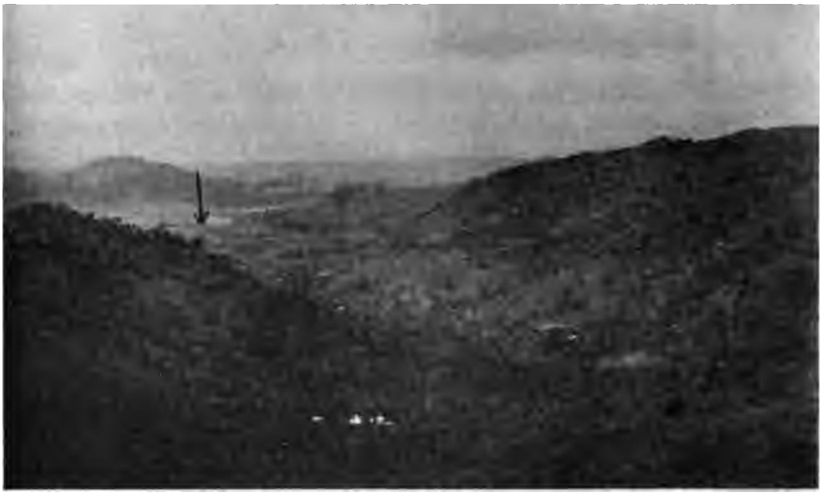


FIG. 22.—*Valley of the Guamani*
Photographed by Professor Charles P. Berkey.

Coamo is dissected to a depth of 50 feet in this way—a testimony to the rapid rejuvenation which has taken place.

The coastal pattern appears to be due in part to the coastal deposits as shown by the present growth of the south coast. Offshore coral reefs are being built. Inside of these land-derived silts are accumulated until the water is shallow enough for mangrove bushes. These form veritable traps for sediment and the sea floor is rapidly transformed to dry land. All along the south shore this is an active process. If one could remove all this built land the angular character of the south coast would be very pronounced. The projections seem to have no relation to present streams; they are not deltas; in fact, they are composed of truncated rock covered with a thin veneer of coastal plain. A tentative theory is proposed—the southwest shore of each of these prongs has a trend practically parallel with the general structure of the region. Moreover, if the various resistant strata were continued to the sea they would in each case follow these projections. When the region was submerged, subsequent valleys were drowned and the ridges between were planed by the advancing sea. Then

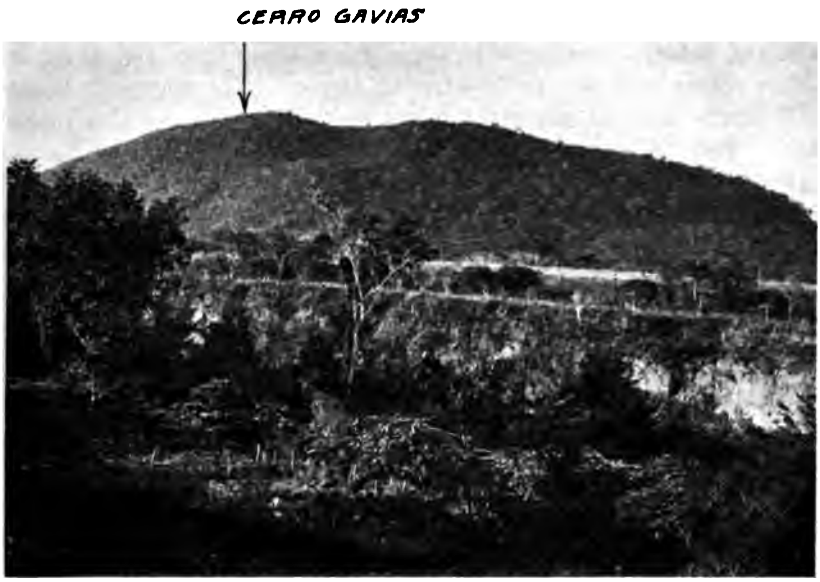


FIG. 23.—*Cerro Gavias, Coastal Terrace, Coamo River*
Photographed by Professor H. E. Crampton

the uplift of 250 feet came, which was not sufficient to fully resuscitate the drowned portions which form the embayed portions between each projection. The combined results of drowning and marine planation have produced the angular coast lines.

GENESIS

The withdrawal of the sea to its present position exposed a series of terraces covered by a mantle of sediment. This mantle is called a coastal plain, though it is commonly misnamed playas (Grabau, 1913).

The coastal plain is a heavy black alluvial silt deposit and is looked upon as delta material deposited beyond the cutting edge of the advancing sea which carved the southern coastal terrace. After being deposited as deltas, littoral currents swept the material along shore and so spread a thin veneer over the whole wave-cut terrace. The mangrove bushes undoubtedly were an important factor in the formation of this coastal plain. Their ramifying branches caught the silts and caused the sea bottom to be rapidly brought to the surface. Thus part of the Central Aguirre Harbor near Pta. Carchones within the last five or six years has had a fringe of land built out from the shore over 200 meters and the mangrove belt has advanced seaward an equal distance.

EARLY INTRUSIVES, FLOWS AND PYROCLASTICS

OCCURRENCE

The earliest intrusive igneous rocks occur as innumerable dikes and sills cutting the older series and as occasional flows and as fragments in tuffs and volcanic breccias.

The rocks of this series will be discussed in two divisions. The first described will be the composition rock types, and the second the structural types.

COMPOSITION TYPES

The following composition types will be described: rhyolites, feldspathic andesites, augite andesites, olivine andesites, basic augite andesites, olivine-free basalts and olivine basalts.

Rhyolites.—Rhyolites are extremely rare and occur widely separated as thin flows. Most of the rhyolitic types were observed as occasional fragments in volcanic tuffs and breccia in the younger rocks of the older series.

The hand specimens are mostly aphanitic, though a few show quartz grains as large as 1 mm., and flowage structure is well developed. The color varies from gray, bluish-gray to buff and all are more or less mottled by iron stains.

In thin section a few of these rocks prove to be glasses. Patic substance varies from 75 to 90 per cent, which is colorless, shows excellent flow lines and contains many blebs and bubbles. In most of the thin sections the quartz cannot be certainly distinguished from the feldspars. In some, however, small .03 mm. euhedral quartz crystals occur. Tabular clear feldspar of the sanadine variety is the rule, but orthoclase and even albite are frequently found, which are usually kaolinized. Magnetite and titanite occur. Secondary minerals are limonite, kaolin, sericite and leucoxene. Some of these rocks are devitrified, as shown by the microaphantic but not isotropic groundmass, and these rocks are much affected by epidotization and carbonation.

Feldspathic Andesites.—The feldspathic andesite rocks occur as small dikes, as thin sheets or flows and as parts of volcanic tuffs and breccias throughout the entire district and cutting all the sedimentary formations of the older series. While their distribution is universal, they do not occur in equal abundance in all parts of the area. Thus, in the eastern part of the district they are about the only rocks to be found, but to the westward, andesites of other varieties increase in number until in the extreme western portion feldspathic andesites are found infrequently. In other words, feldspathic andesites are more numerous in the proximity of the granite batholith and appear to be diaschistic dikes.

These rocks, as found in the field, show grains which are rarely larger than 3 mm. and very few of them are aphanitic. Where glassy substance is present it is only found by microscopic study. Most of the rocks are hiatal—that is, show crystals of marked larger sizes—but few show a perfect gradation between the grains of various sizes. The minerals as a rule, have a tabular or prismatic habit and some have a true granular shape. Only phenocrysts of plagioclase appear, which are usually tabular, though at times they are prismatic. Rarely do the plagioclases occur in groups, but when they do, two or more are crossed like the letter *X*, and some are striated. The colors of these phenocrysts vary from pure white to pale green when fresh. The color of these rocks as a whole is decidedly light green, though darker green is common and other colors are gray and buff. Commonly the green color is not uniform, but within the pale green spots of much darker green occur. These types upon weathering simply get a darker green, though the feldspars at times take on a reddish color due to iron stains. Epidote areas are common and these begin to develop just about the feldspars. The rocks are frequently fractured and the fractures cemented with calcite or in some places by epidote. Some contain vesicles which are usually about 4 mm. long and filled with calcite, which is white or pink. Microscopic study shows the structures of these rocks to be extremely variable. Some are equigranular, others are decidedly hiatal, but most of them occupy positions between the two extremes. By far the largest number are seriate porphyroid. The larger grains rarely get above 3 mm. in size, the average larger crystals or phenocrysts are about 3 to 5 mm, and the smallest grains in the groundmass are .05 mm. The phenocrysts seldom make up more than 25 per cent of the rock; the average is 10 per cent. In some rocks the crystals have no definite arrangement, but in most the crystals in the groundmass have a true pilitic texture. Rarer types have diabase texture and extremely rare types have fine granular texture.

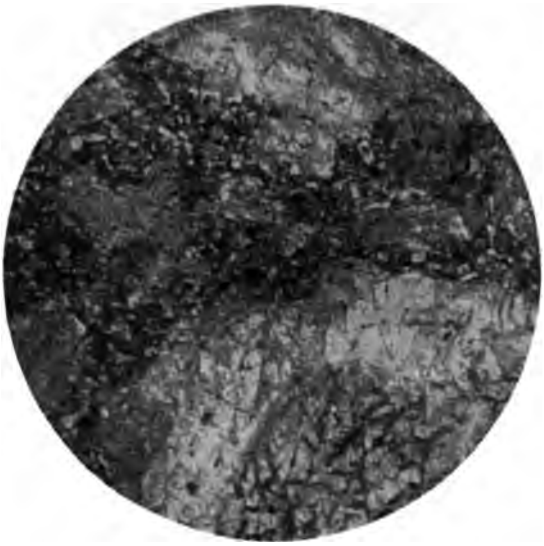


FIG. 24.—*Felspathic andesite*

The feldspars present in greatest abundance are of the oligoclase-andesine variety. They are tabular to prismatic, dull, at times highly altered even to complete replacement, frequently embayed by the groundmass, and often containing inclusions of the groundmass. The twinning lines are irregular and uneven. Very commonly the feldspars are cumulophyric. The feldspars are extremely susceptible to alteration and in fact it is a rare thing to find a fresh one. The change to chlorite takes place readily and especially in the case of the smaller crystals. In this variety of andesite, where the groundmass is highly feldspathic, it is usually entirely altered to chlorite; hence the green color of all these rocks. The feldspars also alter very readily to calcite. In some this alteration has proceeded to such an extent that they are commonly mistaken for limestones. Other alterations affecting the feldspars are changes to secondary quartz, epidote, actinolite, and zeolites which are hydrothermal effects.

The feldspathic andesites are almost a single primary mineral type. The only other primary constituents are magnetite and apatite. The magnetite is often euhedral and averages 5 per cent in amount (Fig. 24). The fillings of the amygdules will be discussed under hydrothermal effects.

Augite Andesites.—Rocks of the augite andesite variety are very rare in the eastern portion of the Coamo-Guayama district. In the central part, compared to the feldspathic andesite, they occur as two to one and in the western third as three to one. They are not confined to rocks of any particular age, but occur as small dikes, sills and flows in rocks of all ages. Sills especially are abundant; augite andesites occur most profusely as components of the tuffs. The two best occurrences of columnar rock are of augite andesite, one of which occurs about three miles north of the La Lapa and the other on the Aibonito-Comerio Road at K. 40. The several occurrences of pahoehoe lava are of augite andesite. Augite andesites are found about the several volcanic centers and are especially abundant about the volcanic center east of La Lapa. The augite andesites therefore are by far the most abundant igneous rocks in the district and make up the major part of the pyroclastic sediments. The size of the grains in these rocks is characteristically small, usually below 3 mm. in their largest dimension, and a few of the rocks have components so small that their crystallized character cannot be determined with a hand lens. The few types which are in part glassy were only so determined by microscopic study. Over 80 per cent are porphyritic, and of these but a small portion are augite porphyries or with phenocrysts 5 mm. or larger. The fabric is most variable; some are decidedly hiatal—*i. e.,* composed of two types of grains differing greatly in size. In some the grains are of uniform size. In most of these rocks the grains are tabular or prismatic and have pilitic or diabasic texture. In a few rare types the texture is truly granular. In some of the rocks of this type only augite phenocrysts are to be observed. These are usually equant or equant-tabular, of dark-green color, and the augites are fresh and clear and more or less perfect in form. The feldspars when observed are usually tabular or tabular-equant, rarely prismatic, and frequently many are grouped together and commonly two or more feldspars are crossed like the letter X. Striations are rarely present. The color is sometimes white, usually gray or greenish-gray. Weathered portions of these rocks do not, as a rule, show augite crystals, but their former presence is attested to by euhedral cavities and within the rock the augites are fresh and clear. This is remarkable in view of the fact that even in the freshest portion of these rocks the feldspars (as shown by microscopic study) are highly altered. The feldspars in the weathered parts of the rocks are usually firm and take on a pink color, due to iron stains, and are therefore easily mistaken for orthoclase. The color of these rocks is almost always green, at times greenish gray, more rarely gray, black, brown, purple, violet, or buff; some are cream.

A few of these rocks are vesicular. The vesicles are round or elongated and may reach 2 cm. in size. The average size is 5 mm. and usually the cavities are filled with chlorite and calcite. Some in addition have fillings of secondary quartz, actinolite, epidote, zeolites and hematite. Because of the great number of these rocks they are very difficult to describe microscopically. No two of them are just alike. The fabric is mostly seriate intersertal to seriate prophyroid. A few are seriate prophyritic, especially those with a glassy base. The phenocrysts make up on an average 25 per cent of the rock. The arrangement of the crystals is varied, but the pilitic type of texture prevails, and diabasic and diverse is common (Fig. 25). The maximum size of the phenocrysts is 4 mm. Usually the feldspars are the larger crystals which are of the oligoclase-andesine variety. These feldspars are tabular to prismatic and irregu-

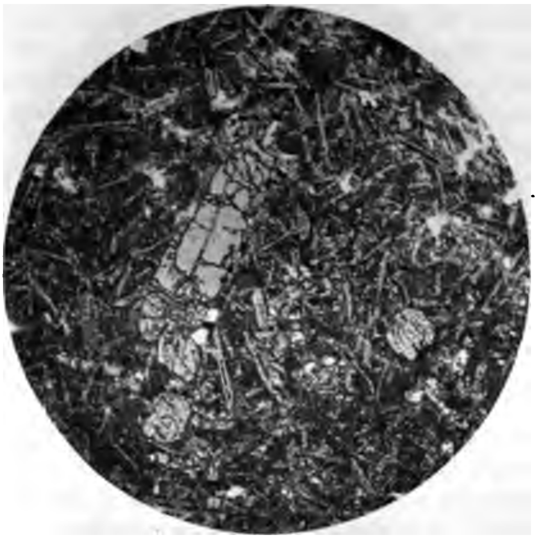


FIG. 25.—*Augite andesite*

larly twinned. Some have Carlsbad twinning superimposed on the albite. The feldspars of the groundmass rarely show twinning and are very prismatic. Frequently the feldspars are zonal and cumulophyric. Some contain inclusions of the groundmass and some are embayed by the groundmass. A little orthoclase and labradorite occur. All the feldspars are dull and most are partly to completely altered to chlorite, calcite or zeolites. As phenocrysts the feldspars rarely exceed 5 per cent, but their great abundance in the groundmass brings the per cent up to 60. Augite is the most common phenocrystic mineral. It occurs up to 25 per cent chiefly as phenocrysts, though a second generation of augite is always found in the groundmass. The largest are 3 mm. in size. The augites are equant to tabular, euhedral, highly cleaved, fractured, sometimes twinned, pale green, fresh and clear. Often perfectly fresh unaltered augites are found in a rock where the feldspars are entirely altered (Fig. 26). Upon weathered surfaces, however, the augites are the first to alter. Therefore, the freshness of the augite and the alteration of the feldspar in a rock is sure proof of hydrothermal alteration, for no other influence could affect rocks not exposed to the surface. The augites are characteristically cumulophyric and commonly contain inclusions of groundmass, bubbles and magnetite. Magnetite occurs in large and small grains, usually euhedral. Aside from apatite, no other primary minerals occur. Calcite, chlorite and quartz are the common secondary and frequently the

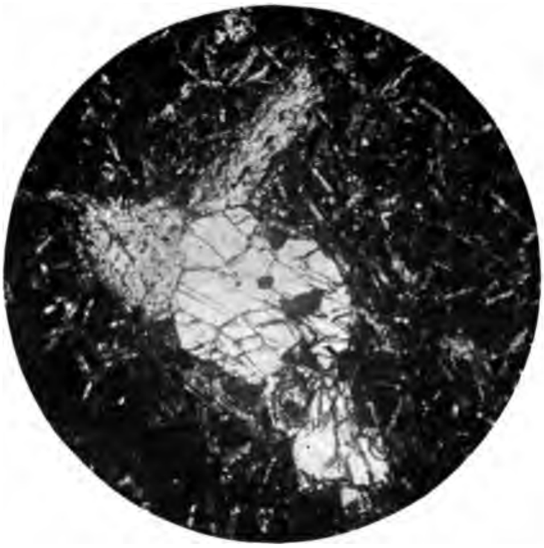


FIG. 26.—*Augite andesite showing feldspars completely altered; augites unaltered*

predominating minerals present. Introduced zeolites, epidote, antinolite, and quartz are frequently seen.

The glassy varieties of the augite andesites occur only as portions of tuffs and volcanic breccias. In these the structure is decidedly porphyritic. Dark brown glass forms 70 per cent of the rock, which contains abundant vesicles and crystallites and shows a well-developed flow structure. The feldspars form 10 per cent of this rock and are tabular twinned, clear and are of the oligoclase-andesine variety. Augite up to 15 per cent occurs in small euhedral pale green, cleaved, fractured fresh grains. Apatite and titanite also occur. Leucoxene and chlorite are developed in small amounts. These paloganites or augite andesite vitrophyres cannot be other than the former glassy scum formed on the surface of some lava-filled crater (Fig. 27).

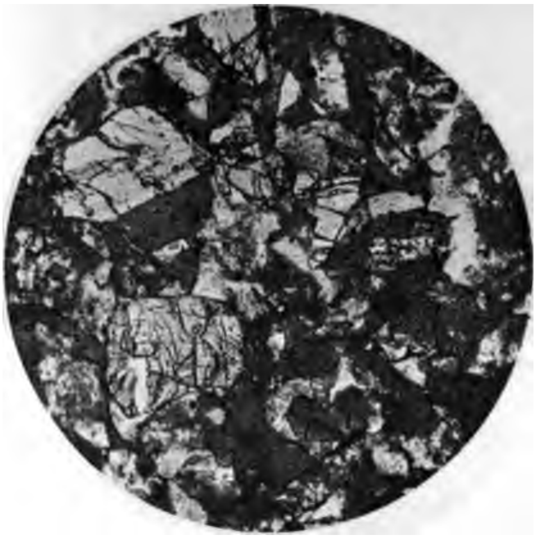


FIG. 27.—*Glassy-augite andesite*

Olivine Andesites.—Andesitic rocks containing olivine are not abundant, though several notable occurrences of them were observed. Thus north of La Lapa is a large exposure occupying the bed of the Rio de la Lapa for half a mile and in the vicinity of a volcanic center east of La Lapa they are common as dikes and they occur throughout the central and western half of the district as dikes, sills, flows, or as fragments in tuffs and volcanic breccia.

The hand specimens of these rocks look very much like the augite andesites, from which they differ only by the darker colors of the groundmass and the presence of olivine instead of augite crystals. The groundmass is gray, dirty green or chocolate and iron stains are very common. When the olivine is present it occurs as tiny 1 to 2 mm., euhedral crystals, but usually the olivine is altered and its former presence is shown by cavities of olivine shape filled with limonite.

The microfabric of these rocks is seriate intersertal to seriate porphyroid. Phenocrysts make up 37 per cent of the rock. The largest grains reach 3 mm. Since augite also occurs in these rocks they might be considered as basalts, but we place in this group all the rocks in which the quantity of the feldspars is three times the femag constituents. The feldspars are oligoclase-andesine with some labradorite. As phenocrysts they do not exceed 5 per cent, but since they are extremely abundant in the groundmass their average percentage is 70. The oligoclase-andesine occurs in prismatic crystals with regular twinning lamellæ. They are altered to calcite and much stained by limonite. The augite is the usual pale green, fresh, twinned, cleaved, fractured, cumulophyric crystals with chadocrysts of magnetite and makes up 10 per cent of the rock. The olivine grains are small, about one or two mm. occurring only as phenocrysts. When fresh they are euhedral, but usually they are completely altered to serpentine, limonite and hematite. They are very cumulophysic and make up 5 per cent. Magnetite occurs as large irregular grains, frequently intergrown with augite, amounting to 5 per cent.

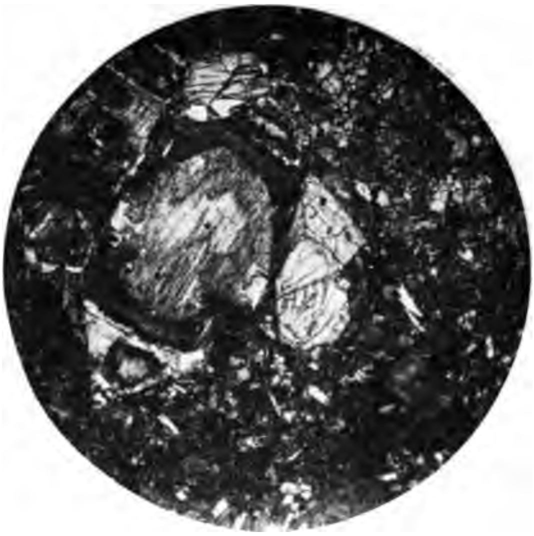


FIG. 28.—*Olivine andesite*

Hematite, limonite, serpentine, secondary magnetite are the alteration minerals (Fig. 28).

Basic Augite Andesites.—Only two occurrences of basic augite andesites were observed, both as dikes cutting the lower parts of the older series. The matrix of this rock is aphanitic and dark dull grayish green. Small 2 mm. dark green, almost black, equant augites and 5 mm. laths of pale green feldspar form the phenocrysts. The microscopic appearance of these rocks is very similar to the augite andesites described above, from which they differ in the greater percentage of femag minerals. Thus in the augite andesites the ratio of feldspars and femags runs 70 to 30 and in these 65 to 35. The fabric is seriate porphyroid and the arrangement of the crystals is diabasic. Phenocrysts form about 40 per cent of the rock. The feldspars are of the andesine-labradorite variety. Some oligoclase also occurs. The feldspars are tabular, irregularly twinned and zonal, and contain inclusions of brown glass. They occur in groups and are strongly affected by chloritic alterations. As phenocrysts the feldspars form 30 per cent of the rock and the augite 13 per cent. The phenocrystic augites are tabular to equant, subhedral, fresh and cumulophysic. In the groundmass the feldspars are extremely prismatic, fresh and form 9 per cent. The augites of the groundmass form 14 per cent, are equant, fresh, highly cleaved, pale yellowish green, nonpleochroic and interstitial. Magnetite in large 4 mm. equant grains

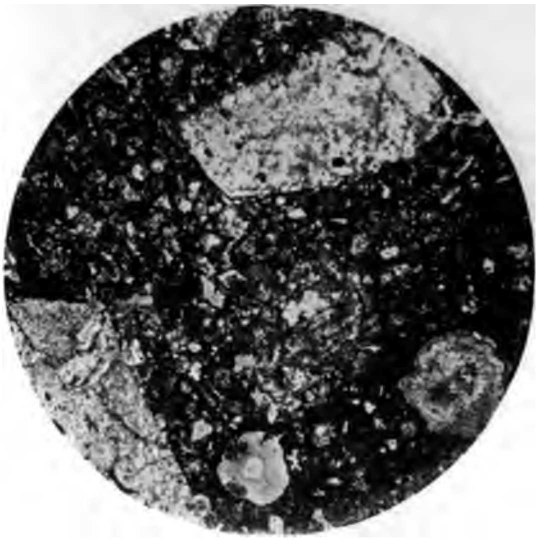


FIG. 29.—*Olivine free basalt*

forms 8 per cent and a few grains of apatite occur. Chlorite developed along cleavage plains in the feldspar is the only secondary mineral. Some of these rocks are amygdaloidal with calcite fillings.

Olivine-free Basalts.—The only occurrence is a vesicular flow near a boss of granodiorites northeast of Coqui. Considered megascopically it is slightly porphyritic, with light to dark gray feldspars occurring in a dark gray matrix. Small amygdule areas filled with white calcite are present. The fabric of this rock is seriate porphyritic. Phenocrysts of feldspars 1 mm. in size occur in a consertal groundmass and are chiefly andesine-labradorite, which are tabular crystals made up of broad twins of variable width. As phenocrysts and as groundmass the feldspars make up 60 per cent of the rock. About 30 per cent of bytownite anorthite occurs, which is similar to the other feldspars except in extinction. Nearly 10 per cent of .05 mm. equant grain of augite are present. Calcite, chlorite and hematite occur as secondary minerals (Fig. 29).

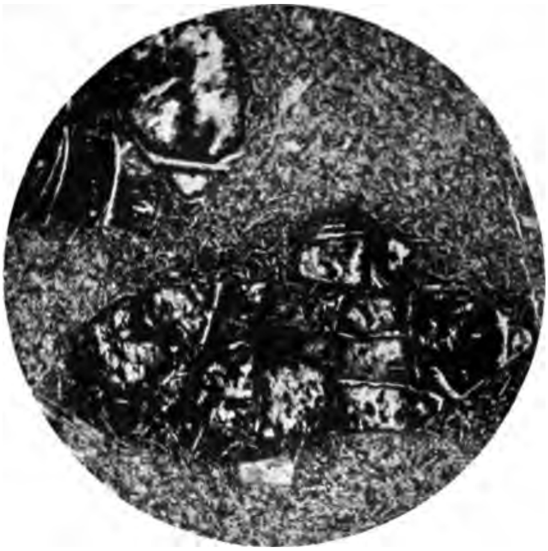


FIG. 30.—*Olivine basalt*

Olivine Basalts.—The olivine basalts are found frequently among the tuffs or as flows, dikes or sills of the older series. The color of the matrix is very dark gray, purple or reddish. The phenocrysts are 3 mm., equant to tabular dark green augites, 5 mm. tabular, striated, light green feldspars, and rusty pits of olivine shape. Most of these rocks are either vesicular or amygdaloidal (Fig. 30). A study of the thin sections shows some of them to be basaltic vitrophyres which have a decidedly hiatal fabric. Phenocrysts make up 50 per cent of the rock. In part the groundmass is microaphanitic. The basic glass is grayish yellow, though in part it is greenish, probably due to chlorite alterations. The yellowish glass is crowded with tiny bubbles, globulites and perlitic cracks. The phenocrysts consist of large 1 mm. crystals of bytownite-anorthite, 10 per cent of andesine, and 10 per cent of labradorite. All the phenocrysts are tabular, broadly twinned and altered along twinning planes to chlorite. Clear, fresh equant pale green euhedral augites occur, amounting to 10 per cent. Olivine entirely altered to serpentine reaches 5 per cent and a few grains of magnetite are always present.

The holocrystalline types of olivine basalts have a seriate porphyritic fabric and possess phenocrysts, which make up 35 per cent of the rock. The feldspars which range from andesine to bytownite are tabular, broadly and irregularly twinned, dull, zonal, resorbed and at times completely altered to chlorite and carbonate. The augites are clear, equant to tabular, euhedral, pale green and cumulophyric. The euhedral olivine is dull or entirely altered to limonite, magnetite, chlorite and iddingsite (?), The groundmass is made up of "fern magnetite"—that is, magnetite crystals in parallel growth and untwinned laths of feldspar. In total the olivine makes up 12 per cent, augite 10 per cent, magnetite 15 per cent, and feldspar with secondary products the remainder of the rock.

SPECIAL STRUCTURAL TYPES

Some of the above-described composition types take on structures which deserve special mention. There are many occurrences in Porto Rico of volcanic flows filled with pyroclastic materials. These flows are either augite andesite or feldspathic andesites. Scattered throughout the igneous matrix are lithic fragments and sedimentary fragments. Some of these rocks are crowded with introduced fragments, as, for example, the beautiful rock exposed in the stream bed just east of Cayey. The fragments show little or no absorption, but they do show at times contact phenomena. Thus euhedral .05 mm. pale greenish-yellow garnets form rims around the feldspars and occur scattered irregularly throughout the groundmass (Fig. 31). Other examples of flows filled with breccia are found east of Coamo, just south of Cidra, near the northward bend of Rio de Cuyon and just west of Comerio. True flow breccias were found which belong to the augite andesite or feldspathic varieties. In thin section they are seen to be composed of angular fragments lying in irregular positions, in a matrix of the same composition. The best example was found south of Cidra (Fig. 32).

The most interesting types of compound rock are conglomerates with an igneous matrix, of which several fine examples were observed. An accessible occurrence is between K. 86 and K. 78 on the Military Road; another is found where the Rio de Cuyon turns westward, but the very best extends in the bed of the Rio Jajome for nearly a mile in the Jajome Gorge. Others were observed north of La Lapa, and southwest of Comerio, and east of Barros. These formations show typical conglomerate structure. Pebbles and boulders occur in layers, semi-oriented, and between them the finer pebbles show torrential bedding. Viewed from a distance, the igneous character of the matrix would not be suspected

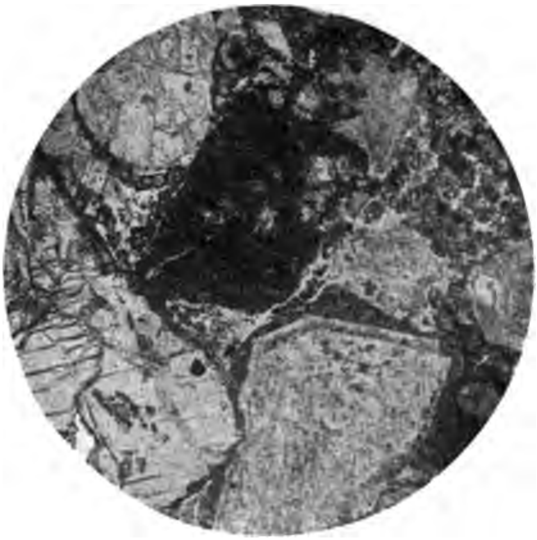


FIG. 31.—*Lava flow containing pyroclasts of calcite which are surrounded by garnets*

(Fig. 9). Critical pieces selected and examined microscopically show good igneous structure (Fig. 33). This structure might have been developed by metamorphism, but this is disproved by the unmetamorphosal character of the under or over lying beds. Moreover, the same conglomerate traced along the strike changes to formations with a sedimentary matrix. The matrix is undoubtedly primary igneous rock and was locally introduced, which would be possible in several ways. A valley filled with conglomerate boulders or a fan of conglomerates might have had a flow of lava pass over it. This lava would sink into and fill the interstices and so cement the borders. In view of the perfect sedimentary matrix of the same conglomerate beds elsewhere, it is unlikely that the portion with a conglomerate matrix was free of tuff or interstitial silt matter, the presence of which would have prevented the lava flowing over the surface to seep downward. The preservation of the torrential bedding and the sedimentary matrix in part argues against a lava flow picking up pebbles and boulders and carrying them with it down a slope. The only reasonable explanation is that first assigned by Berkey for the occurrence on the Military Road. From a fissure below these conglomerates lava issued and soaked slowly upward into the conglomerate, producing in it, locally, an igneous matrix. This lava must have been extremely fluid, and this is quite possible, in view of the fact that in all occurrences the matrix is an augite andesite, to be able to seep upward and replace the sedimentary matrix without disturbing the original torrential structure. The invading lava, in greater part, replaced the sedimentary matrix, for all test specimens show no trace of former clastic fragments and there seems to be no other view to take than that the lava was able to assimilate the finer clastic material, which was probably due to the fact that the heat of the lava was effectively protected from radiation by the heavy blanket of sediments overlying the conglomerate. In places, such as the north of La Lapa and in the Jajome Gorge, some of the pebbles appear to show a transitional boundary with the matrix. Wherever exposed in a stream bed the conglomerate affords a most pleasing appearance. The augite andesite matrix, highly altered to chlorite, forms a green background into which boulders of every size and color are set.

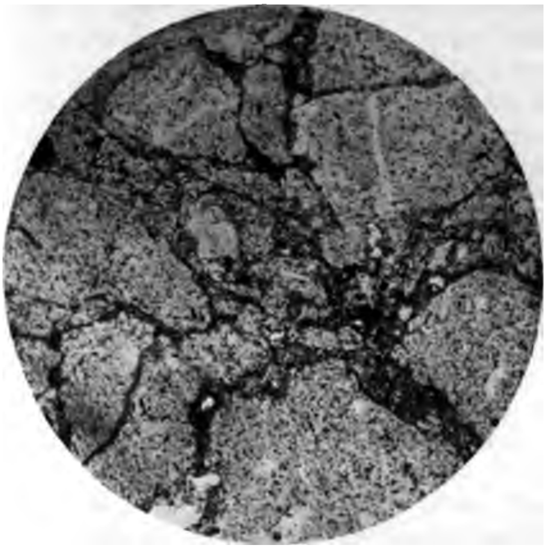


FIG. 32.—*Flow breccia*

Vesicular or amygdaloidal structures are found in feldspathic andesites, augite andesites, basic augite andesites, olivine-free basalts and olivine basalts. These types, therefore, are all surface flows. The absence of this structure in the hornblende-bearing rocks is in accordance with the view expressed on a later page—that the hornblende is the deep-seated equivalent of the augite. Rocks of this character are not as common as one might expect in a region where volcanic action of a surficial nature has played so important a rôle. Strictly vesicular flows are extremely rare. Pahoehoe structure is to be found in the northern portion of this district. Good exposures of augite andesites, outcropping on the Comerio-Aibonito-Barros Road, show this feature very well. In some cases the structure is accentuated by the fact that at the time of the flow tuffs were falling and the tuffs have served to separate the various billows of lava one from the other. Columnar structure was observed in two places, between K. 40 and K. 41 on the Comerio-Aibonito Road, and another at the head of the Rio de la Lapa. Both are developed in augite andesites. In the latter exposures the columns are bent in their middle, as shown in the accompanying sketch (Fig. 34). The total thickness of the augite andesite at this point is nearly 30 feet and the individual columns are about 14 inches thick. In the sketch the solid lines show the actual body observed: *a* to *g* are cooling surfaces of equal temperature, and since the columns must develop normal to these cooling surfaces it

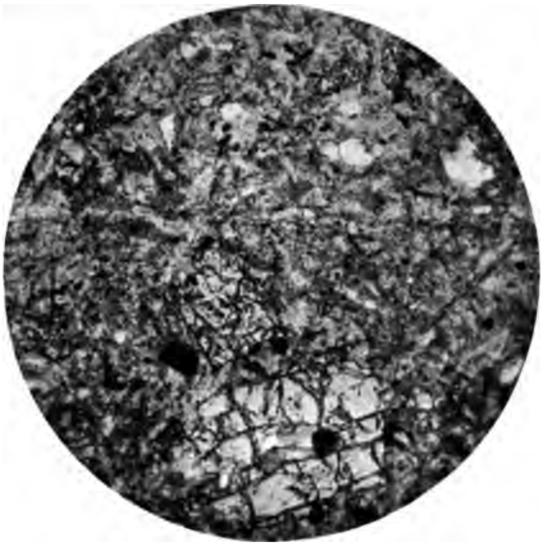


FIG. 33.—*Igneous structure of the Sierra de Cayey conglomerate matrix*

will be seen that near the end of every flow there must exist a position where the columns will be bent, as shown in the figure.

GENESIS

All the rocks described above are considered early differentiates of the batholith which is exposed in the eastern end of the island and which extends westward beneath the Coamo-Guayama district. If all the types could be averaged the composition would probably be that of an augite andesite, a rock which may be considered to represent the composition of the magma reservoir from which they were derived. Since the sediments in the Coamo-Guayama district were derived from rocks of the same composition, the view cannot be held that the composition of the underlying magma was due to their assimilation. The composition was either primarily augite andesite or made so by assimilation of rocks not exposed in this terrain.

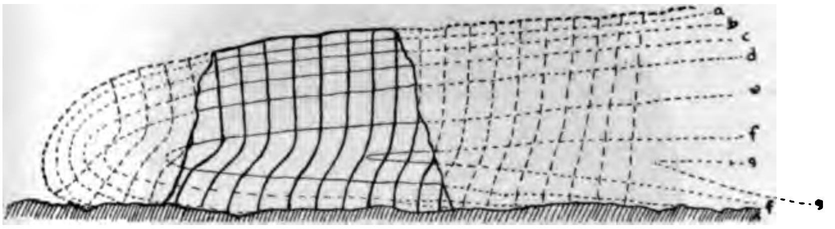


FIG. 34.—*Relation of isothermal surfaces to andesitic columns*

BATHOLITHIC ROCKS

OCCURRENCE

The greater portion of the batholithic rocks lie beyond the limits of this district and enter it only as a somewhat detached mass occupying the hills just west of Guayama.

GENERAL CHARACTER

The general character is described by Berkey (1915, p. 28):

> The most prominent type of intrusive mass is that seen in the southeast portion of the island, including the district about Huamacao and Yabucoa and Las Piedras and Juncos. Whether or not this is all one mass belonging to a single intrusion has not been determined. The variety of composition seen in the different samples, taken at different points, is consistent with the presence of more than one intrusive unit; but it is also possible and quite as likely that

the variety observed is wholly due to magmatic differentiation. The southerly portion of this mass, especially that near Yabucoa, is represented by a very coarse, very quartzose and almost pegmatitic granite. Farther to the north, in the vicinity of Las Piedras Juncos, the rock has the appearance of a syenite. Although a part of the rock does show the composition of a true syenite, by far the greater number of specimens collected on this expedition show the presence of quartz in sufficient amount to make the rock a granite. It would appear, therefore, that this occurrence in the southeast portion of the island is essentially a granite mass and that it is of unusually large size, reaching practically from the coast at Maunabo to Caguas. The distance across this mass is, therefore, not less than about 12 miles north and south. In all probability it is not of quite so great an extent east and west, but these boundaries are unknown.

The portion adjacent to this district is not coarse enough to be a true granite. Micropegmatitic structure is characteristic. Traced toward the Coamo-Guayama district it becomes dioritic in composition and the grain becomes finer until at Guayama the extreme border is an andesite in composition and texture.

Hornblende Granite.—Hornblende granite is the only type which enters the Coamo-Guayama district. The hand specimen appearance is mottled, due to grains which are of equal size and irregular form. Areas of dark green hornblende 1 to 3 mm. in size are separated by larger areas of quartz and feldspar. The feldspar is either white, pale pink, or pale green. Under the microscope this rock is holocrystalline and equigranular. The average size of the component crystals is 2 mm., which is almost too small for a granite. The rock consists of 30 per cent orthoclase intergrown micrographically with quartz. Feldspar of the albite-oligoclase variety occurs to 20 per cent. The feldspars are faintly kaolinized. Quartz occurs as part of the microscopic intergrowth and as euhedral grains. The latter contain numerous lines of bubble inclusions. Quartz makes up 40 per cent of the rock. The hornblende occurs in prismatic crystals, is cumulophyric and makes up 5 per cent of the rock. The hornblende is in part bleached and in part altered to epidote and chlorite. Other primary constituents are titaniferous magnetite altered to leucoxene and apatite. Some limonite stains occur and the rock is highly altered in part to epidote, and needles of actinolite (Fig. 35).

GENESIS

Whether the batholith is a satellite or the peripheral portion of the primitive batholith, it must represent the residuum left after the separation of the augite andesites and basalts. Whether it is injected without solution or whether it is invaded by dissolving the country does not matter, for in the latter case it would only assimilate a small portion of the rocks, eliminated as intrusions and extrusions in an earlier period. Such assimilation would increase its basicity but little; it would return to a stage in its magmatic history a little previous to its present one. Because the apophyses of this batholith are of intermediate composition and quantitatively small, to return all apophyses to the batholith would increase slightly its basicity; therefore, at the time of its injection the composition of this batholith was probably grandioritic or monzonitic. Hence, if in turn we add the large number of augite andesites and the few basaltic types, the composition of the primitive magma is obtained, which would be dioritic.

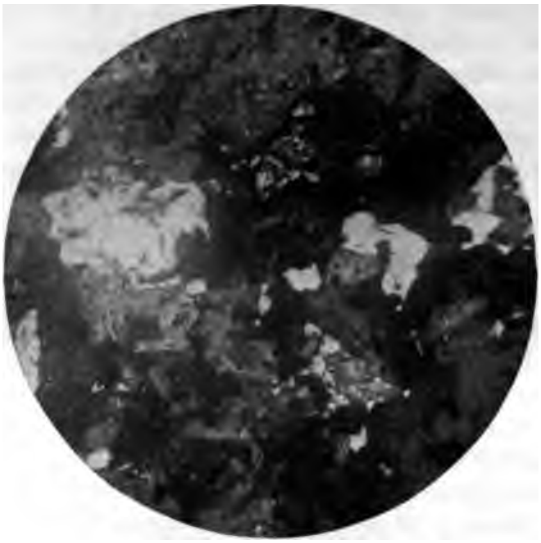


FIG. 35.—*Hornblende granite*

LATER INTRUSIVE ROCKS

OCCURRENCE

Rocks of this series occur as large intrusive dikes and stocks throughout this district. They bear undoubtedly a diaschistic relation to the batholith. The composition range in this group is from biotite granodiorite to hornblende andesite, which is a greater range than exists between the extreme of the earlier intrusives.

Biotite Granodiorite.—Just north of where the Rio de Cuyon turns and flows westward is a boss of granodiorite which cuts the Barranquitas-

Cayey series. A group of hills east of Coqui is formed by a boss of this rock, the marginal phase of which is diorite and near its base a dike of augite andesite and a flow of vesicular olivine-free basalt are found (Fig. 36). Megascopically the rock consists of 2 to 5 mm. masses of dark green biotite and occasional specks of hornblende or pyroxene in a white to light green field of feldspar. In some varieties the quartz is not apparent in the hand specimen. In thin section the rock is equigranular and made up of grains which average 5 mm. in size. Oligoclase in dull, tabular, subhedral, twinned crystals amounts to 55 per cent. Some of the oligoclase is twinned according to both the albite and Carlsbad laws. The biotite occurs in brown and green cumulophyric intergrown patches amounting to 15 per cent. Much of the biotite has gone over into the chlorite. The first occurrence mentioned above has 5 per cent of clear, colorless augite, the second a small area of green hornblende. In the former the quartz occurs in interstitial material, in the latter as multiform grains with many strings of inclusions. In both, quartz is present to about 20 per cent. Equant grains of magnetite and prismoids of apatite and zircon occur. Sericite is secondary and epidote an introduced mineral.

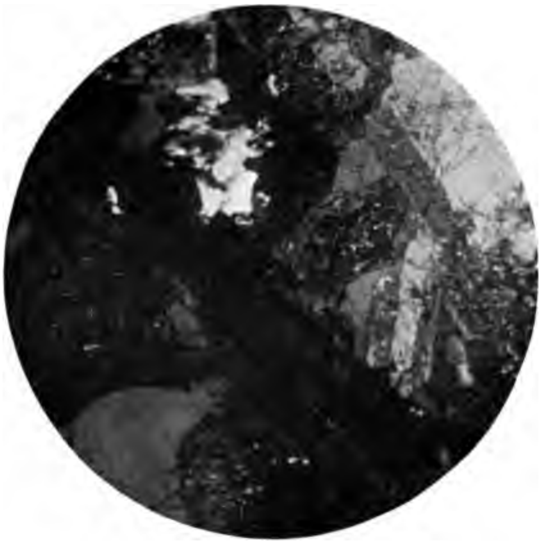


FIG. 36.—*Biotite granodiorite*

Hornblende Diorite.—Rocks of this type occur throughout the older series as bosses or thick intrusions. They are more common than their finer-grained equivalents, the hornblende andesites, suggesting a genetic relation existing between depth and the occurrence of hornblende. As observed in the field the size of the grain ranges between 2 mm. to 5 and 6 cm., the average being 3 mm. With few exceptions the rocks are composed of grains of equal size and these are thoroughly intergrown. In some, however, the hornblende crystals get very large; a few have been observed which were 6 cm. long. The hornblendes are decidedly prismatic, black and fresh. The feldspars are tabular, rarely striated, and vary in color between white and pale green. Generally the hornblendes occur as interstitial matter between the feldspars. A few grains of magnetite are common. The microscope shows the essential structure of these rocks to be seriate homeoid, and composed of grains averaging 1 mm. in size. About 50 per cent of this rock is made up of tabular 1 mm. euhedral, broadly twinned crystals of andesine. Most of these andesines are fresh and clear, though a few are slightly altered to chlorite and zeolites. A few crystals of labradorite, less of orthoclase and many of oligoclase occur. The hornblende is pale green, subhedral, and pleochroic, occurs interstitially and cumulophyrically, and contains chadocrysts of feldspar. Around the borders of the hornblendes are large numbers of magnetite grains. The hornblendes have very ragged borders and the magnetites occur within the shadowy former border of the crystals. Apparently the magnetites are left as a residuum after the dissolving away of the hornblende borders. Hornblende makes up 25 per cent of the rock. About the border of the hornblendes and occurring apparently as recrystallization substances are tiny augite and calcite crystals. Magnetite occurs in

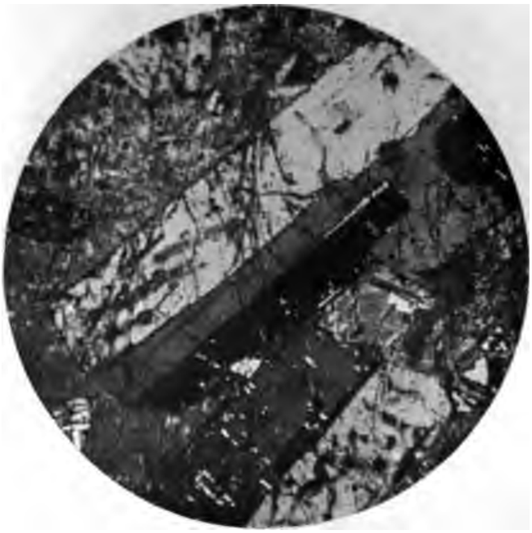


FIG. 37.—*Hornblende diorite*

large areas with chadocrysts of feldspar. Apatite also occurs as a primary mineral. The feldspars are altering to calcite, sericite and secondary quartz (Fig. 37).

Hornblende-Augite Diorite.—Just south of La Lapa several dikes of this variety of rock were observed. Considering the large number of augite andesites, it is remarkable that no augite diorites were found; or, to view the matter from another point, the large number of hornblende diorites is in striking contrast with the very few hornblende andesites. In hand specimens the hornblende augite andesites are made up of holocrystalline, equigranular, intergrown 3 mm. areas of dark green hornblende with smaller white feldspar areas. Under the microscope this rock appears seriate porphyroid with the largest grains reaching .05 mm. The feldspars are chiefly andesine with some oligoclase and make up about 50 per cent of the rock. The hornblende is all altered to chlorite and in and near the chloritic areas, still retaining the hornblende shape, are small crystals of augite. Some of these augites are cumulophyric. The augite therefore appears to have been derived from the hornblende. Long 1.5 mm. needles of apatite occur. The feldspars are zeolitized and secondary quartz is present (Fig. 38).

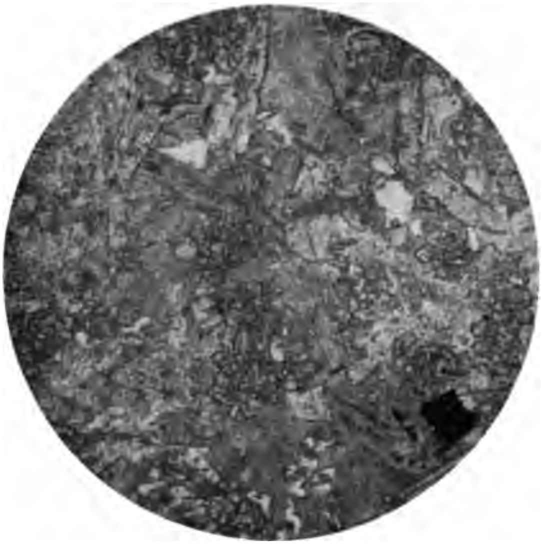


FIG. 38.—*Hornblende-augite diorite*

Hornblende Andesite.—Hornblende andesites occur as thick dikes. A fine one is exposed on the Aibonito-Coamo Military Road, between K. 97 and K. 98, and several dikes occur south of the Coamo Reservoir dam.

In all occurrences the rocks are coarse, almost hornblende diorites. No specimens were observed in the volcanic tuffs. Hand specimens show grains which may approach 4 mm.; the average is about 1 mm. except in a rare occurrence which has a divitrified groundmass. The fabric is, as a rule, hiatal, with large phenocrysts of plagioclase and hornblende occurring in the groundmass, which may be light or dark green, gray, pale blue or dull gray. The plagioclase crystals are tabular, rarely striated and sometimes crossed. The hornblendes are black, shiny, and highly prismatic.

Under the microscope the fabric is usually found to be seriate porphyroid, though a few may be seriate porphyritic. The larger crystals, commonly in the case of hornblende, reach 5 mm. in size and the feldspars 3 mm. The crystals of the groundmass may be so small that the texture is microcrypto-crystalline, as in the case of one hornblende andesite with a divitrified matrix. The most common texture is diabasic. The phenocrysts are hornblendes and feldspars. The hornblendes are euhedral to subhedral, prismatic, dark green, usually cumulophyric, and highly altered to chlorite and epidote. Some contain chadocrysts of magnetite, which commonly shows octahedral parting. Magnetite amounting to 5 per cent also frequently occurs secondarily as a product of reorganization about the ragged borders of the hornblendes. The feldspars are of the oligoclase-andesine variety, with the emphasis on the andesine, and aver-

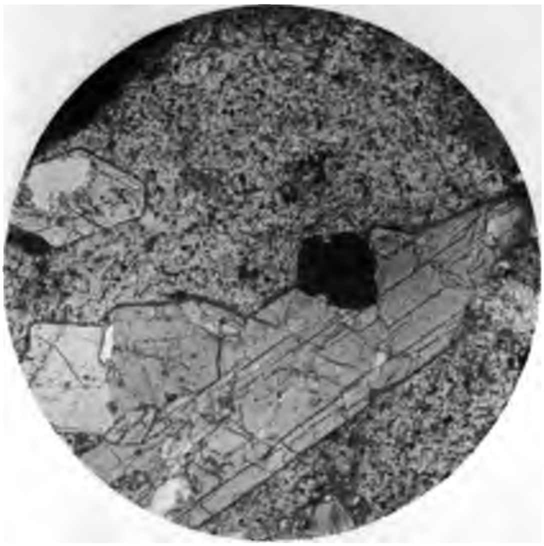


FIG. 39.—*Hornblende andesite*

age 16 per cent. One or two per cent of orthoclase occurs at times and an occasional crystal of plagioclase. The feldspars are irregularly twinned and zonal. Their shape is tabular, as phenocrysts, or prismatic in the groundmass. The phenocrystic feldspars are commonly cumulophyric, crossed and highly altered to chlorite and calcite. Magnetite occurs in equant crystals up to 5 per cent. Other primary minerals are apatite, pyrite and ilmenite. The groundmass is composed of feldspars and magnetite and generally is entirely altered. The ratio of groundmass to phenocrysts is 66 to 34. Other secondary minerals are zoisite and leucoxene (Fig. 39).

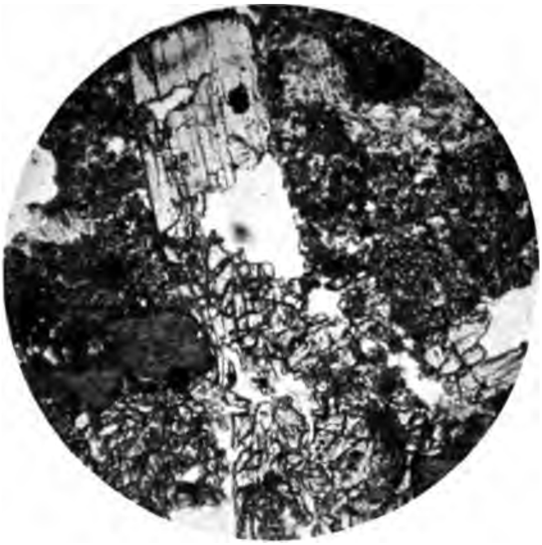


FIG. 40.—*Hornblende-augite andesite*

Hornblende-Augite Andesite.—Dikes of this rock occur among the augite andesites and are particularly common near La Lapa and north of the Baños de Coamo. These rocks in hand specimen show 3 mm. phenocrysts of hornblende. These are set in a light green matrix of feldspar laths. In thin section they are seriate-intersertal. Augite crystals form the largest phenocrysts, amounting to 10 per cent. They are pale green, clear, fractured, and cleaved; the hornblendes are prismatic and green and are altering rapidly to chlorite. The hornblende occurs both as phenocrysts and throughout the groundmass as shreds. The total amount of hornblende is 10 per cent. Oligoclase-andesine in euhedral, zonal-twinned, prismatic, dull crystals make up 60 per cent. Magnetite and apatite occur (Fig. 40).

GENESIS

The rocks discussed above are thought to be diaschistic dikes given off by a batholithic mass which underlies the Coamo-Guayama district. The range in composition is greater than in the earlier intrusives, which is due to the fact that a batholith which ascends to higher levels will show greater differentiation than at lower levels. This is due to the greater time for differentiation and the wider range in temperatures and pressures. The larger intrusives are more acid; the largest observed were of biotite granodiorite and the smallest were of hornblende andesite—that is, the nearer the intrusives approach in size to the batholic rocks the more acid becomes their composition, or the nearer the diaschistic dikes are eroded to the batholith the more their composition approaches that of batholith. The succession of these various intrusives was not determined. Among the older andesites were a few hornblende andesites. The hornblende diorites are always thick dikes and much more common than hornblende andesite. No augite diorites were found, but a few hornblende-augite diorites were observed. In all these, as described above, the augite is reorganized from the hornblende, and the hornblende often shows reorganization to magnetite and secondary augite. Such facts show that hornblende as a mineral is genetically related to higher temperatures and pressures, and augite to lower temperatures and pressures.

Conclusions as to the Ages of the Various Series

SEDIMENTARY ROCKS

In the above paragraphs two pronounced unconformities have been described. One exists between the Baranquitas-Cayey and the Sierra de Cayey series, beneath which some fossils were found and which give a clew as to the ages of the older rocks. A short distance below this unconformable contact two calyxes of a coral were found in a limestone which have been identified as *Cladophyllia furcifera.* Ordinarily this form is considered a typical index fossil for the Edwards division of the Fredericksburg group of the Comanche in the Gulf region. Its presence here should indicate that the rocks are at least of Comanche age. Below the limestone occurs a thin bed of bog iron ore and in it were some leaves. Dr. Edward W. Berry and Dr. F. H. Knowlton identified these leaves as follows:

Nelsonia, an old Mesozoic order of cycads.
Protorhipis, a fern with same range as above.
Another species of Mesozoic fern.
A dicotyledon.

The above authorities stated that these plants were not critical for the Comanche, but that they tended to support the evidence of the corals—at least they indicate Mesozoic age. In addition to the above, at several horizons some radioliaria, foraminifera and diatoms were found[3] as follows:

Textularia gibbosa, d'Orbigny.
Textularia conica, d'Orbigny.
Textularia triochus, d'Orbigny.
Pleocanium (*Textularia*) *speyeri* (Reuss).
Operculina sp.
Orbitoides papyracea, fragments.
Orbitoides faujasii, Sowerby, fragments.
Paralia (*Melosira*) *sulcata,* Ehr.
Coscinodiscus elegans grev?
Parodiscus concentrica (*Flustrella concentrica,* Ehr).
Lithocampe with seven joints and flatly compressed edges (Fig. 5).
Orbulina universa, d'Orbigny?

Textularia gibosa is a form well developed in the Miocene and early Tertiary and *Textularia conica,* d'Orbigny, is common today in the coral reefs of Porto Rico. However, *Textularia,* as a whole, is characteristic of the Lower and Upper Cretaceous; *Operculina* and *Orbitoides* occur also in the Cretaceous. Radiolarian forms, though very numerous in the Miocene, are well known to occur far back in the geological scale and *Orbulina universa* is common in the Upper and Lower Cretaceous. Thus while some have great range, yet in view of the fact that the most common form, *Textularia,* is generally Comanche or Cretaceous, it is probably safe to say that these smaller creatures also support a Comanche age for this system. I conclude, therefore, that the above rocks are Comanche in age.

Immediately above the Sierra de Cayey and Barranquitas-Cayey contact the only fossils found were several *Orbitolites* forms, which signify but little. About two miles north of the Rio Jueyes Water Gap and close to the Rio Jueyes River, in a very calcerous tuff, was found one specimen of *Venericardia alticosta.*[4] In the Gulf States this is considered an index fossil for the Jacksonian and Claibornian formations of the Upper Eocene. But some fossils which are indices of certain horizons in one place are often found to belong to beds of older age in other regions. This may prove to be the case with *Venericardia alticosta.*

Large numbers of foraminifera, radiolarians and diatoms were found in these rocks. In all cases the minute organisms were only discovered in thin sections and for that reason their determination in many cases was found impossible. Sufficient were determined to testify very strongly to an Eocene age for these rocks.

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[3] Identified by Rufus M. Bagg.

[4] Identified by Prof. A. W. Grabau.

The types observed follow:[5]

Foraminifera:

- *Orbitoidea papyracea* (Boubee).
- *Textularia gibbosa,* d'Orbigny.
- *Globigerina bulloidea,* d'Orbigny.
- *Truncatulina lobatula* (W. and J.).
- *Meliolina seminulum,* Linné?
- *Textularia* sp.
- *Gandryina* sp.
- *Polymorphina* sp.
- *Miliolina* sp.
- *Biloculine* sp.
- *Numulites* sp.
- *Orbitoides* sp.
- *Amphistegina* sp.? (Fig. 19).
- *Discorbina globularis,* d'Orbigny.
- *Globigernia* sp.? (Fig. 42).
- *Ostracods* sp.?
- *Heliodiscus humboldti,* Ehr?
- *Porodiscus concentricus,* Ehr? (Figs. 20 and 41).

Diatoms:

- *Melospira arenaria,* Rab.
- *Coscenodiscus marginatus.*
- *Melosira* sp.

Among the above fossils *Porodiscus concentricus* is of *early* Tertiary age (Fig. 41), as is *Amphistegina* (Fig. 19). As a whole, this group of minute forms and *Venericardia* indicates Tertiary and some point directly to the Eocene. Apparently the Eocenic is in the older series. That this is so is further shown by the age of the next succeeding group of rocks.

The Eocene age of the uppermost rocks of the older series has some bearing on the problematical presence of the Cretaceous. For, in view of the universal presence of Cretaceous rocks in the islands of the West Indies which have been studied, it seems fair to assume Cretaceous rocks in the Coamo-Guayama district. There may be an unconformity between the Eocene and Cretaceous (?) which was not found in the limited time devoted to this study.

The next great break is the discordant unconformity separating the Rio Descalabrados formation and what little remains of the Arecibo in the Coamo-Guayama district. The age of the Arecibo is rather definitely fixed. Fossils were collected from it on the north coast by Mr. R. D.

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[5] Identified by Rufus M. Bagg.

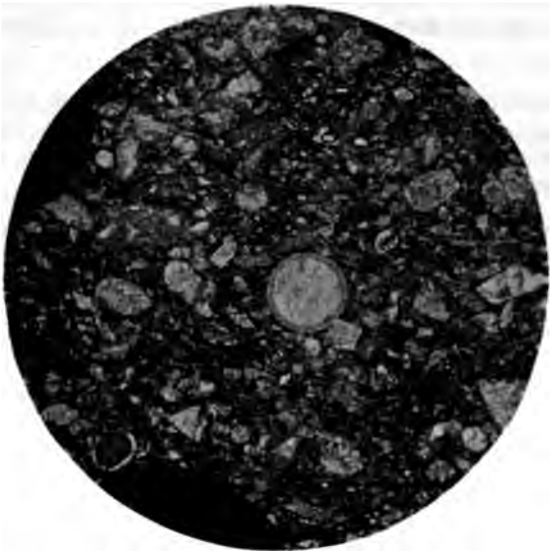

FIG. 41.—*Porodiscus concentricus in tuffaceous shale*

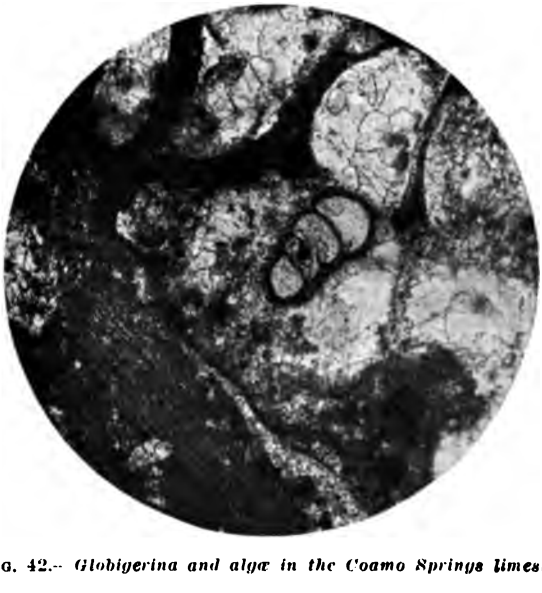

FIG. 42.—*Globigerina and algæ in the Coamo Springs limestone*

Semmes and from it in the south coast by Prof. Charles P. Berkey. Both collections were identified by Dr. W. H. Dall. On the north coast were found:

Metis trinitaria (Dall), an index of the Bowden formation, Upper Oligocene of Jamaica.
Pecten sp.
Haminea sp. Very abundant.
Cypraea sp. Abundant.
Amauropsis sp.
Conus sp.
Ampulina sp.
Strombus sp.
Orbicella aff. cavernosa (Linné).
Fringed coral, not determinable, but similar to those found in Oligocene of Antiga, Anguilla and Cuba. Dr. Dall considers this an Upper Oligocene fauna.
Metis trinitaria, which is typically Upper Oligocene, is stated by Mr. R. D. Semmes to occur at the base, as well as in the upper portions of this formation.

Professor Berkey collected his fossils west of the mouth of the Descalabrados River, just outside of the area under discussion, and west of Ponce. Care was taken to gather them from the base of the Arecibo limestone, which is the younger series of Berkey.

These were identified as:

Lucina sp.
Lucina sp., much like forms from the Chattahoochee.
Pecten sp., like *Pecten thetidis* (Sowerby).
Fasciolaria.
Amauropsis ocalina, similar to forms in the Ocala limestone of the Gulf States.

Mr. R. T. Hill (1899) states that the Arecibo limestone is in part equivalent to the Arecibo on the north coast and though largely Pleistocene, the lower strata may be as old as Oligocene. Of the older series Hill (1899*a*) says: "The rocks of the central mountain region are Cretaceous and possibly of early Eocene age; at least no evidence tending to establish other dates has been as yet discovered." Since these limestones of Upper Oligocene age lie upon a peneplaned surface, they indicate that the Eocene exists either in the great unconformity or is to be found in the older series. The presence of *Venericardia* and the large number of Tertiary foraminifera diatoms and radiolaria seems to suggest that the latter is the case.

If the age of these formations is correctly determined, then a great break lies between the Eocene and the Oligocene in Porto Rico. The character of the Eocene-Oligocene contact in North America is poorly understood. A summary (Cooke, 1916) of the views taken regarding the contact in the area where it is best known shows that the various authorities differ by as much as a whole geological period. Could this divergency of view be explained by the existence of an unrecognized unconformity?

The Santa Isabel formation is undoubtedly recent in age. Fossils collected from railway cuts and from terraces south of Coamo Springs were compared with specimens washed up on the south shore of the island and for every fossil species an identical one could be found among the types still living. The stratified character of the fossil horizons, the presence of corals and sponges, and the total absence of human artifacts led to the conclusion that the fossils found were deposited by natural agencies and that their presence indicates an elevation of very Recent origin.

IGNEOUS ROCKS

The igneous rocks appear to be divisible into three age groups. In the first group they occur mostly as dikes, flows, sills and volcanic fragments of which augite andesites were found in greatest number. This is shown by their dominance in the early tuffs, by their presence as flows in the older series, where they occur as intrusions, and by their comparative rarity in the vicinity of the granite batholith. Types such as basic augite andesites, olivine-free basalts and olivine basalts, in so far as these rocks occur, are to be found under similar conditions. Feldspathic andesites are to be found in the older tuffs, but in view of the great number bearing a peripheral relation to the granite batholith, it is more reasonable to postulate a later period at which a great many of the intrusive feldspathic andesites developed.

The second group is younger. The granite batholith cuts Comanche and Cretaceous sediments and probably, though it cannot be proved, cuts Eocene sediments. The point which is important is that the igneous rocks classed in the first group occur as component parts in sediments which are cut by this granite batholith. The top of this batholith is truncated by the peneplane developed in Porto Rico and the invasion of the batholith is, therefore, antecedent to the peneplane.

The direct evidence that a third stage exists are the dioritic and hornblende andesite dikes which cut the batholith at various places, notably north of Virella. Throughout the Coamo-Guayama district biotite granodiorites, hornblende diorites, and hornblende-augite diorites occur. These are so different in character from the rocks known to belong to the first stage and so like those which cut the batholith that the inference is that they are genetically related to the granite batholith and later in age. The feldspathic andesites are best developed close to the batholith, and seem to be, therefore, apophyses of it. Not all the augite andesites can be proved to belong to the first stage. Some of them may have been given off in the third stage.

SUMMARY OF AGE RELATIONS

The following tabulation summarizes the age relationship of the various rocks:

The Older Series.	Rio de la Plata series Barranquitas-Cayey series	Comanche.
	Sierra de Cayey series Guayama series Early intrusives Rio Jueyes series Coamo Springs series Rio Descalabrados series Batholithic rocks Later intrusives	Cretaceous to Eocene.
The Younger Series.	Arecibo formation Santa Isabel formation	Oligocene to Recent.

HISTORICAL SUMMARY

Under the heading of "genesis" and elsewhere, the geological history of the Coamo-Guayama district has been described in detail. Here only a summary of the more salient events will be given.

Early Period to End of Comanchic Time

The very existence of Porto Rico is dependent upon a volcanic past. This much can be said from the character of the sediments which are of pyrogenic materials, slightly reworked or not reworked at all. That the island has been built up from the ocean bed by the accumulation solely of volcanic debris is to be doubted. The more probable view is that the vulcanism which produced the sediments was only a superficial expression of the major organic forces which elevated the whole West Indian region in early Comanchic (?) time. The embryo Porto Rico may even have stood above sea-level when the first volcanic activity began. The practical absence of glassy types in oldest known pyroclastic rocks, or, for that matter, in any of the rocks, seem to indicate relatively slow cooling, which would not take place in the cold water of the profound ocean depths.

The earliest record in the Coamo-Guayama district shows intense vulcanism. The materials ejected or poured out had little or no reworking. Quiescent periods occurred during which the sea advanced over former sites of deposition, as is shown by the several beds of limestone which are free of tuff fragments. During the latter portion of this era vulcanism apparently decreased, for the uppermost rocks are reworked tuffs and ashes.

CRETACEOUS AND EOCENE

The deposits accumulated in previous times of intense volcanic activity were reworked and redeposited during this period. The Sierra de Cayey period was one of sudden and pronounced uplift. The uplift, which was either that of a broad arch or a fault block, revived all of the streams, and the result was the creation of great alluvial fans which sloped down from the mountain toward the south. This uplift was probably not very great. A small change of elevation will cause decided erosion. At the time under consideration the elevation was probably not much greater than at the present time. The essential factor in rejuvenated erosion is that at times the stream becomes torrential and carries down a mixed load of boulders and silts, followed by a period when the stream is incapable of removing the boulders, but can separate out from among them the finer material. Thus in the present flood-plain deposits and in the course of the Salinas River large boulders occur in great profusion, many of which are as large as any occurring in the older measures. The same conditions are exhibited on the Coamo River and several streams on the south coast.

The alluvial fan condition, initiated by the Sierra de Cayey period, continued through the Eocene. After the first impulse of rejuvenation had worn itself out, the streams eroded and transported finer materials on a reduced grade. Periodic outbursts of vulcanism developed tuffaceous measures. Slight oscillations of the Porto Rico block permitted the sea to advance inland for periods long enough to develop thin limestone beds. As a whole, however, the data testify to a very little diastrophic movement. Most of the limestones were formed in embayments between great alluvial fans and developed synchronously with shales brought down by rivers or tuff intermittently thrown out by volcanoes. As the island was gradually worn lower and lower, the batholith underlying the Coamo-Guayama district, except in the southeastern corner where it outcrops, was gradually working its way upward. Long before the end of the

Eocene the upper portion of the batholith had come so close to the surface that it froze and was partly eroded. At the close of the Eocene the general baseleveling, which had been in progress since the end of the Comanche, eventually reached its highest degree of perfection in a peneplane and the land surface became so low that the sea was enabled to advance over it.

OLIGOCENE

At the time of the marine transgression vulcanism must have been absent; otherwise the basal portion of the coastal deposits would contain much volcanic débris and the limestone would contain many tuffaceous inclusions. Neither of these conditions are conspicuous enough to have been observed; on the contrary, the base of the coastal plain deposit is a carbonaceous shale. This carbonaceous basal shale indicates that the sea advanced rapidly over an area pretty well worn down. If the sea had transgressed slowly a perfect sorting of materials would have ensued from marine-planed old rock and this would have given conglomerates, sandstones and shales. But if there existed a peneplane, covered with a deep residual soil and supporting a heavy growth of tropical vegetation and the sea advanced rapidly, then only a carbonaceous shale, followed by limestone deposits, would have been formed. The result of the overlapping sea was the deposition of a heavy limestone formation.

MIOCENE TO PLEISTOCENE

The first event after the deposition of the limestones was uplift. Berkey (1915, p. 40) writes as follows:

> The physiographic habit of the island as a whole tends to support the view that the fundamental structural form is that of a large fault block, with the principal fault displacement and uplift along or near the southerly margin, tilting the whole mass gently northward. If this disturbance took place, as seems to be indicated by the fault described, in very late Tertiary time, accompanying the emergence from the sea, it would account for the abnormalities of Tertiary rock distribution as well as the unsymmetrical position of the main drainage divide. In any case, however, the fault block structure is a very late development and is superimposed on the other more complex and older structures of the mass.

The next event was the removal of the Arecibo and dissection of the underlying older series. So completely has this been performed in the Coamo-Guayama district that only one outlying hill remains of the Coastal Plain limestone deposits. Dissection has continued to the present time and brought the district to a state of maturity and has been accompanied by stream adjustments, but without equal success, for the streams are about as imperfectly adjusted as possible.

PLEISTOCENE (?) AND RECENT

Judging purely by analogy, Porto Rico suffered first a major uplift in the Pleistocene (?). This first movement, intended to satisfy internal earth stresses, probably not only compensated these stresses, but overreached its mark and produced others of an opposite nature. To relieve these latter stresses, oscillatory movements of the island are now taking place. The frequent earthquakes throughout the West Indies are part of this phenomenon. One effect has been to cause a recent elevation of the island. But before this recent uplift took place the island remained stationary for a considerable period, during which the Caribbean carved a platform far into the island. Thus west of the Coamo-Guayama district a terrace is cut into the Arecibo Oligocene limestones. However, the total cutting in the whole island was so little that nine-tenths of it still remains mountainous. When the sea had finally finished its carving the shore stood much farther inland than at present and the site of the Guayama was beneath the sea and those of Salinas and Santa Isabel were between 50 and 60 fathoms deep. The surface of the Caribbean was nearly awash with the tops of the Aguirre Hills, Salinas Hill and Monte Sebater. Great bays were formed in the valley of the rivers, one of which extended up Guamani to about K. 24, another reached La Lapa in the vicinity of Salinas, a third reached as far north along the Rio de Coamo as the Baños de Coamo, and the great subsequent lowland behind the Coamo Springs limestone range was a salt marsh. Those hills which stood as islands during the sea's farthest advance, or as reefs 25 feet or more above the sea bottom, became surrounded on all sides by the coastal plain and some sediments now all eroded away may have been deposited upon them. The isolated hill southwest of Coamo Reservoir, the low hills southwest of Salinas Hill, Salinas Hill itself, Monte Sabater and Aguirre Hills and the hills near Melonia Reservoir are now islands in the coastal plain technically called mendips or morros. The high hills east of Guayama were at one time mendips, but erosion of the coastal plain to the north has converted them into peninsulas extending into a coastal plain.

After the sea had advanced as far inland as described above, uplift occurred in two successive stages. The result was the formation of two terraces. The second uplift followed closely upon the first, because the sea-cliff cut is small and the size of the lower terrace is much the larger.

VULCANISM

Volcanic centers are typical features of the Coamo-Guayama region and of many other parts of Porto Rico. In this district volcanic vents were observed in the following places: South of the Coamo Reservoir, about a mile south of the Rio Descalabrado Water Gap, between K. 98 and K. 99, and between K. 87 and K. 88 on the Military Road, several on the Rio de Cuyon east of the bridge on the Military Road crossing it at K. 93 and a very large and complex one east of La Lapa. The one, south of Coamo Dam on the Military Road, can be seen in cross-section. There the strata are cut by numerous intrusions, mostly of a dioritic character; the sedimentary beds have been shoved, crowded, broken and thrown out of their former attitudes and the intrusive dikes contain large irregular fragments of the sediment, which are hydrothermally altered. Tuff accumulations occur irregularly between the sediments and the dikes. On the Descalabrado, where a volcanic vent is to be seen in plan, the same features are shown and in addition the rocks are highly fractured and cemented by epidote and calcite. The center east of La Lapa shows an old vent, now filled with coarse volcanic breccia, with much tuff and introduced epidote and calcite. Surrounding this vent, within an area of about two miles square, are hundreds of augite andesite intrusives and flows and less numerous dikes and flows of feldspathic andesite and a few hornblende diorites. These numerous intrusives, cutting shales, which are intensely altered hydrothermally, form a complex the structure of which is impossible to decipher. In the bed of the Cuyon a limestone formation is broken through by a vent, which is filled with limestone fragments, andesite tuff and augite andesite lava. With the one exception, between K. 87 and K. 88, all vents cut Eocenic sediments. Older ones undoubtedly existed, but their presence has now been effectively concealed and the only conclusion to be drawn from the location is that vulcanism continued into post-Eocenic time. Of course all the superficial physiographic features produced by vulcanism were wiped away by the post-Eocenic peneplanation.

HYDROTHERMAL EFFECTS

Mention has been made of the highly fractured character of all the Porto Rican rocks. These fractures are usually cemented by introduced minerals. Some rocks, in addition, show metasomatic replacement and a few others are almost entirely replaced. Whether the minerals are simply introduced or in part replaced, all are considered hydrothermal. There is direct evidence in some of the addition of water; in others only certain constituents have been dissolved away, apparently by water, and in many the state of the minerals indicates only the presence of some agent, such as water, which facilitated chemical reorganization without the introduction or subtraction of any component.

The following types of hydrothermal alteration will be considered:

(1) Those in which one or more of calcite, quartz, chlorite and epidote were developed.
(2) Those in which zeolites, calcite and chlorite were formed.
(3) Those in which epidote, quartz, chlorite and actinolite, one or more, were introduced.
(4) Those in which hematite and quartz were introduced.

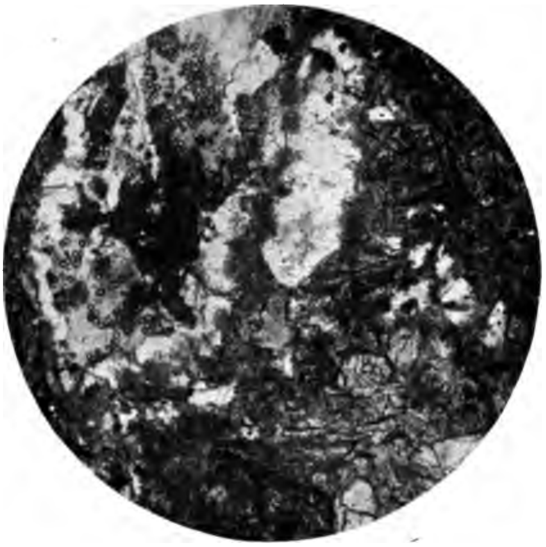

FIG. 43.—*Chlorite developing from feldspars which are associated with fresh augites*

(1) Weathered surfaces of Porto Rican rocks show partial or complete alteration of the femag minerals, especially of the pyroxenes. This is in striking contrast with the clear, fresh, unaltered condition of the same minerals within the body of the rock where weathering influences have not reached. Feldspars, on the other hand, even in the most durable, firm and unweathered rocks, are generally altered. Feldspars are commonly entirely replaced in parts of the rocks far beyond any influence of weathering. Thus in a prospect on the slopes of the Luquillo Mountain where a shaft had been sunk 50 feet below the weathered zone, the feldspars were all altered. The feldspars are universally dull and lusterless and even if exposed on weathered surfaces they are never much more

altered than in the interior of unweathered rocks. The above facts lead to the conclusion that the alteration of the feldspars is related to some internal agency.

Many of the feldspars show little patches within them of calcitic alterations; others are replaced by pseudomorphs of calcite. The feldspathic groundmasses alter easily, frequently and completely to calcite. The feldspars are all calcic and only the addition of CO_2 is required to alter them. Almost every rock shows carbonate and some are altered so completely that, in the case of sills or flows, they are easily mistaken for limestones. This alteration is not confined to igneous rocks, but is found in sediments which contain calcium-bearing minerals. It is not an exaggeration to say that 20 per cent of all the rocks in the Coamo-Guayama district are altered to carbonate. For such an intensive alteration CO_2-bearing water solutions must have been coming up from the depths in great volumes and for long periods of time. The calcite so formed does not always remain in place, but migrates to other rocks or is dissolved out of the rocks entirely. Thus the deposits of tepatate, frequently observed in the stream beds, result from the precipitation of the dissolved calcite and apparently the streams are carrying concentrated solutions of concentrated calcium carbonate to the sea.

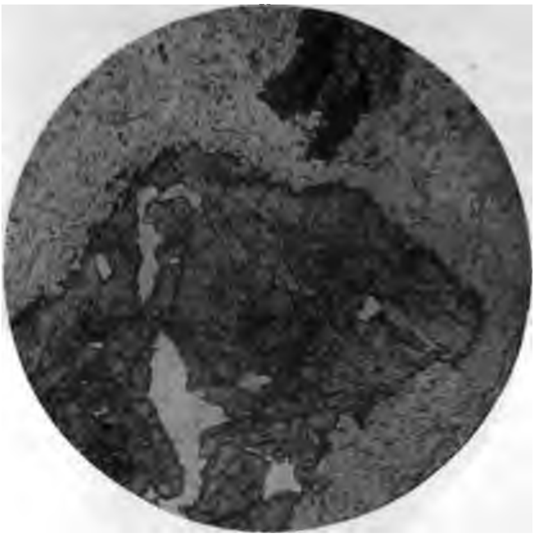

FIG. 44.--*Epidote replacing feldspars*

Hardly less common than the calcite is chlorite. The first place that chlorite develops is along cleavages or twinning planes in the feldspars.

Where well developed it is always in association with the feldspars and shows direct evidence of being genetically related to the feldspars. In the rocks where chlorite is best developed the ferromagnesium mineral augite will be clear, fresh and unaltered (Fig. 43). In the case of chlorite we must grant the introduction of magnesium. Probably water solutions of magnesium carbonate reacted with the feldspars to form $CaCO_3$ and the hydrous magnesium aluminium silicates. The calcite and chlorite are, as a rule, intimately associated as if this were the case. Secondary quartz would be released by such a reaction, and fine-grained secondary quartz is, therefore, very common in these rocks. Epidote at times replaces the feldspars and occurs alone or in association with the above minerals. It can be formed from the calcite feldspars directly by hydration (Fig. 44). (See figure 45.)

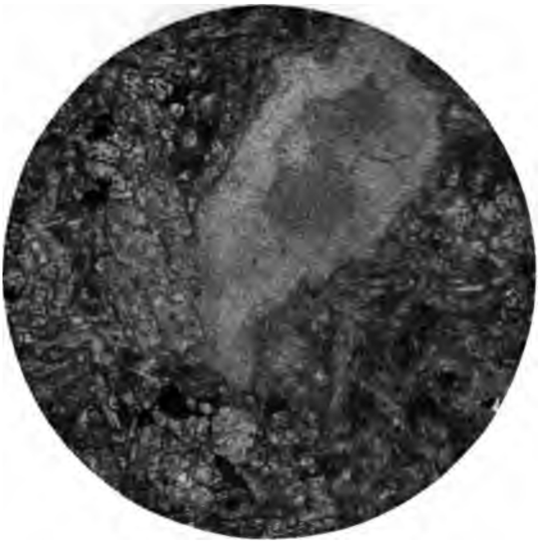

FIG. 45.—*Minerals named in order from the center outwards: stained antigorite, stilbite, laumontite, and calcite*

The phenomena discussed in the above paragraph are principally those of reorganization plus slight additions of magnesium, CO_2 and H_2O. Hot water, however, was the stimulant which occasioned the reorganization.

(2) Closely related to the above alterations are the zeolites. Strange to say, the zeolites were not found filling amydaloidal cavities nor are the zeolites common and they always occur intimately associated with chlorite. Around the periphery of these zeolite-chlorite areas is, commonly, a border of calcite. The shape and the association with more or less altered

feldspars is such as to prove a direct development from the calcic feldspars. Reorganization, stimulated by thermal waters, bearing in addition to magnesium carbonates, also potassium carbonates, would produce chlorite, zeolites, and calcite from calcic feldspars. It appears that of the secondary minerals formed calcite was the most mobile, for it traveled to the periphery of the groups of secondary minerals so formed or even farther (Fig. 45).

(3) The greater portion of the hydrothermal rocks contain the quartz, epidote, chlorite, actinolite and zeolites, one or more, in either vesicular cavities or fractures and the boundaries of these cavities show little or no replacement (Fig. 46). In a few cases the replacement has proceeded to such an extent that the whole body of the rock is a mass of epidote. Though epidote was not the first mineral to come in, it was in many rocks the only one and quantitatively it plays the major rôle. In the types of rock described above epidote can be definitely proved to have developed originally from the feldspars by reorganization (Figs. 44 and 47). Some of the epidote so developed may have migrated and filled the veinlets and vesicles in the rocks of this type. If so, the epidote in some of its occurrences came in from distant, deep-seated sources, for it occurs in veins or in vesicles in rocks which are strictly fresh and unaltered in all other particulars. Moreover, its intimate association with actinolite of undoubted introduction argues very strongly for a deep-seated source (Fig. 46). It

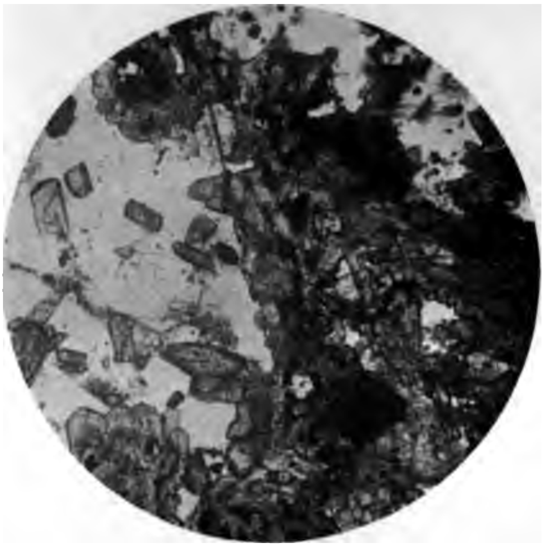

FIG. 46.—*Intimate mixture of quartz, epidote, and actinolite*

is difficult to explain the complete replacement unless introduction was under intense hydrothermal conditions.

All the minerals did not necessarily come in a definite succession. In some rocks (Fig. 46) quartz, epidote and actinolite seem to have come in almost simultaneously. Where the succession is best shown the order is quartz, epidote, chlorite, actinolite and zeolites. In a few rocks epidote occurs on the walls of veins which have a quartz filling, showing epidote to have been introduced first, but the balance of the evidence indicates that quartz began to develop first and continued to come in with the later minerals.

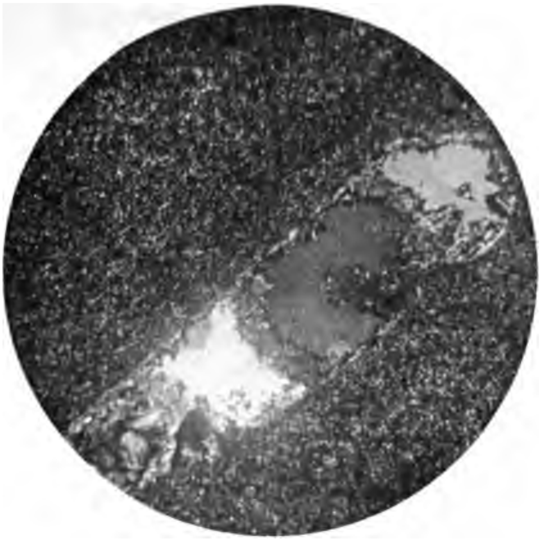

FIG. 47.—*Quartz and epidote replacing feldspar*

Actinolite occurs as isolated needles, as needles penetrating quartz, and as radiating growths and the occurrence of actinolite in such relationships is generally regarded as sure proof of igneous emanations. The actinolite is not stable, but readily hydrates and converts to chlorite. It is metasomatic only in so far as it penetrates quartz—a phenomenon very common in rocks altered by igneous emanations.

An interesting feature, rather common, is the association of zeolites with the actinolite frequently in intimate intergrowth. If the actinolite is an igneous emanation, then the zeolites must also have been introduced by thermal waters at high temperature. Another feature is the extreme development of secondary quartz. Shales are converted entirely to cherts by the quartz. The association of the quartz with the other minerals of this group proves it to be hydrothermally introduced and not the result of reorganization of radiolarian and diatom shells, as is the case in some of the sediments. The sediments show the calcareous shells of foraminifera replaced by secondary quartz. In other rocks calcite of hydrothermal origin plainly replaces the quartz. Evidently inert calcite can be replaced by hydrothermal quartz, but when both calcite and quartz are hydrothermal the quartz has a greater solution pressure and is readily replaced by calcite. In the andesite secondary quartz will develop in aureoles and then by reorganization take on the trapezohedral form. When first observed the writer considered such rocks to be quartz andesites. Further study shows that the quartz is all secondary. It is possible that many of the quartz andesites described in the literature were of this origin.

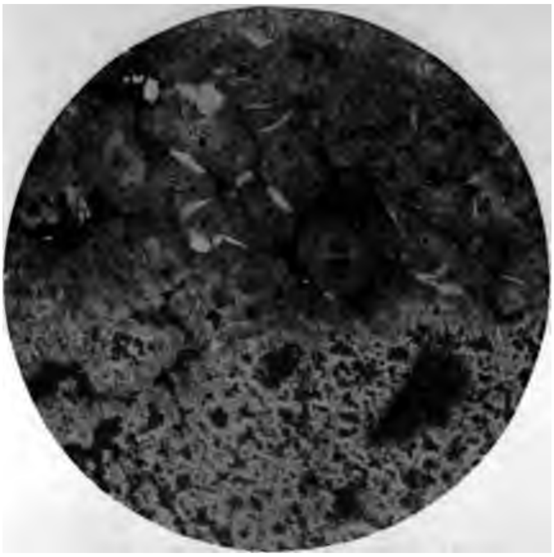

FIG. 48.—*Spherulitic growths of specular hematite and chalcedony*

(4) The fourth type deals with some effects which are interesting because they show a hydrothermal introduction of hematite and because of the possibilities involved if the process were carried to completion. Shales are silicified by spherulitic growths of chalcedony. The growth of these chalcedonic fibers was spherical and nearly equal in all directions and the growth was frequently interrupted, probably due to the intermittant supply of feeding solutions. Synchronously with the growth of the chalcedony spherulites, specular hematite was introduced. It was deposited interstitially, chiefly between the spherules, and when the spheru-

lites were not growing formed a hematitic shell about them. After a period of continued growth of the spherules, another shell of hematite developed, and repetition of this process formed bodies of spherically radiating fibers of chalcedony containing within them and around them concentric shells of specular hematite. After the cessation of chalcedonic growth hematite continued to be introduced and in some cases has metasomatically replaced the fibers of spherules. Where this has taken place bodies formed of a succession of concentric shells of hematite separated by radiating fibers of hematite are cemented together by hematite—that is to say, a typical oölitic structure is formed. The oölitic structure is emphasized in thin sections by the hydration of parts of the shells to limonite (Fig. 48). The petrogenesis of this rock was not worked out until too late to collect critical samples. It is thought, however, that the continuation of this process to completion in a large shale bed should produce a rock that could not be distinguished from oölitic iron ores. Or, to go even further, why could not some of our oölitic iron ores have been produced by hydrothermal action?

The phenomena described in the above two paragraphs are developed best in the vicinity of old volcanic centers. The two best occurrences were found about a volcanic center near the Quintana thermal spring, north of Ponce, and about the La Lapa volcanic center.

MINERALIZATION

Mineralization is a feature considered to be genetically related to the hydrothermal effects and is just as common. Nearly all the rock of the Coamo-Guayama district contains introduced sulphides, mostly pyrite, though chalcopyritic pyrite is frequently present, as shown by the copper carbonate stains on the rocks.

THE COAMO THERMAL SPRINGS

Location and Purpose of Study

The Baños de Coamo is a thermal spring located just north of the Coamo Water Gap and issues through a bed of conglomerate and tuff, which rises as a boss of rock through alluvium (Fig. 49). The point at which the spring opens is about 50 feet above the beds of the nearby Coamo River. Practically no deposits are being formed by its waters. The thermal and mineral properties of the water have for many hundreds of years been regarded as possessing medicinal properties and it is from this fact that it has received the name Baños de Coamo. The origin of its waters is the subject of discussion in this section.

OCCURRENCE OF SPRINGS AND WELLS

Reconnaissance studies over the greater part of the island by the writer and observations made by several geologists over all of Porto Rico indicate that, with this one exception, no springs of any kind are to be found in the older series of rocks. There are many seepages at the bottoms of the débris-filled gullies in the interior mountains after heavy rains. These cannot be considered springs and do not affect our discussion. Not only are springs absent from the older series, but wells sunk into them have never been successful. In the younger series, however, springs do occur at times, and wells are occasionally located. The cause of this relationship is simple. The rainfall upon the interior mountains, formed of the older rocks, does not sink into them, but follows superficial courses down their flanks until the waters meet the cuesta edge of the coastal plain deposits, under which a small part of the water

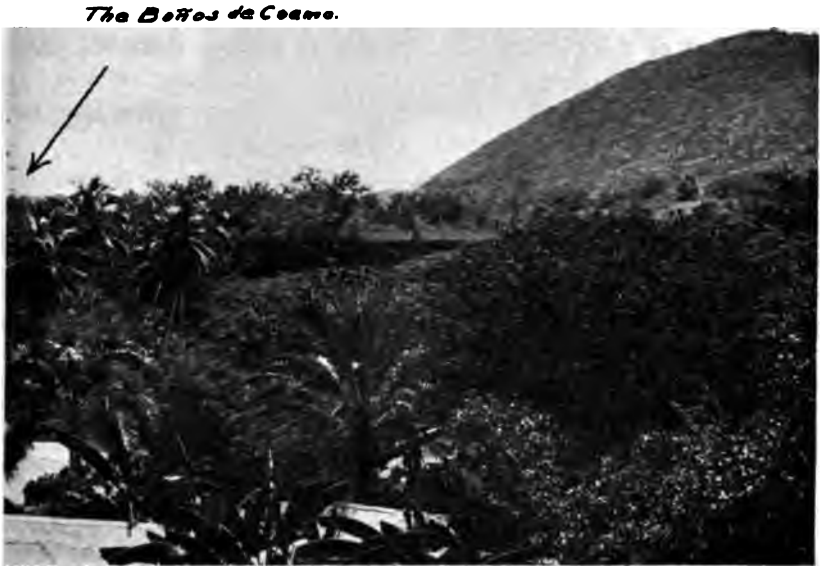

FIG. 49.—*Coamo Springs*
Photographed by Professor H. E. Crampton.

seeps. The waters working between the coastal plain deposits and the bed-rock of the older series give rise to springs or wells. Thus the best wells in the Arecibo formation have been found near thin coastal margins and the best wells in the Santa Isabel alluvium are found adjacent to streams. Does it not appear significant that in the older series there is only one spring and that a thermal spring?

LOCATION NEAR A FAULT

The direct location of the spring is probably due to a fault which strikes north very close to the Coamo River. Berkey (1915, p. 39) describes another fault which may continue into this district, and if it does extend eastward in the same direction it would lie very close to the Coamo Springs:

> The most prominent fault, in its effect upon present features, is the one now marking the inner margin of the "younger series" of chalky limestones and shales constituting the coastal belt along the south side of the island from Juana Diaz past Ponce at a short distance to the north, crossing the Ponce-Arecibo Road at K. 4.8 and thence westward crossing the Ponce-Penuelas Road at K. 10. . . . It must be of very late Tertiary age, because the chalky Ponce beds are abruptly cut off by it. The older rocks of the pre-Tertiary are lifted with respect to the "younger series" forming the present coastal margin wherever this fault has been seen. . . . What becomes of it at either end is not yet determined, but it is believed to extend much farther in both directions.

SOURCE OF WATER

The Coamo Springs may obtain their waters from one or more of six sources, as follows:

(1) Meteoric,
(2) Connate,
(3) Entrapped,
(4) Strayed magmatic,
(5) Secondary magmatic,
(6) Primary magmatic.

(1) Meteoric waters are the waters of rainfall which have descended to sufficient depths to become heated and have then ascended again to the surface.

(2) Connate waters are sea waters which became entangled with marine sediments at the time of deposition and remained locked up in these sediments after the coastal plains had been uplifted and more or less consolidated. The best known example of this is found in the copper mines of Michigan (Lane, 1908).

(3) Entrapped waters are waters of any type which were formerly following some underground channel and as a result of faulting, intrusion of a dike, or the occurrence of some similar event were cut off from an avenue of escape and prevented from reaching the surface. Waters at Butte may belong to this category (Lindgren, 1913).

(4) Strayed magmatic waters are those given off from a magma for the first time and which follow channels not leading to the surface, and so have remained stored underground until tapped by a fault, a valley, or by mining. Such waters, depending upon the length of their sojourn, may develop a composition reflecting the country rock through which they have passed. Some of the waters of the Comstock Lode may be of this type.

(5) Secondary magmatic waters are waters of any type which, as a result of assimilation of rocks containing them by an invading magma or as a result of diffusion into the magma from the country rock, have become incorporated into the magma and have been subsequently given off from the magma.

(6) Finally waters, which were part of the earth's interior magmatic reservoir, may be given off and reach the surface for the first time. Such waters are primarily juvenile.

Where there are so many sources or combinations of sources from which a spring could obtain its waters, it is difficult to decide which is the more probable source.

Possibility of a Meteoric Source

SEASONAL RAINS AND VARIABILITY

The meteoric origin will first be considered. If the waters are meteoric or derived from the rainfall, they should show some relationship to the seasonal rains of Porto Rico. That the rains are seasonal is shown by the following record of a typical station, the Toro Negro station near Juana Diaz.[6]

		Inches
1911.	September	8.60
	October	21.63
	November	6.25
	December	18.14
		53.62

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[6] From the records of the Porto Rican Irrigation Service.

1912.	January	2.82
	February	2.07
	March	3.38
	April	7.50
	May	1.89
	June	1.51
	July	9.46
	August	8.81
		37.44
1912.	September	14.71
	October	25.67
	November	15.06
	December	2.59
		57.83
1913.	January	2.54
	February	2.91
	March	5.06
	April	9.97
	May	8.44
	June	4.03
	July	2.18
	August	3.04
		38.17
1913.	September	13.35
	October	11.80
	November	5.80
	December	2.59
		33.54

This is a typical station as regards variability of rainfall, and it shows that during the four months nearly twice as much water falls as during the eight arid months. Yet despite this great difference in precipitation the Coamo thermal spring shows no noticeable change in volume year after year. Legend tells us that at the time of Columbus it gave forth more water than at the present time, but within the last two generations the flow has been just the same as it is today.

The southern coast of Porto Rico is arid and it is within this belt that the Coamo-Guayama district lies. In 1897-98 for a period of 13 months not a drop of rain fell in Guayama (Wilson, 1899), but the thermal spring, a few miles distant, did not show the slightest variability in its discharge.

FLOODS AND UNDERGROUND CIRCULATION

After one of Porto Rico's torrential rains the streams rise rapidly to floods sufficient to carry boulders, but within a few hours after the cessation of rainfall the streams quickly fall and within twenty-four hours the beds are dry. This phenomenon is particularly noticeable on the south side, where rains are infrequent. On the north side daily rains occur and the larger streams receive new contributions of water before the previous day's rain has been entirely carried away. Nevertheless, upon the tributary streams, which are more sensitive to daily deluges, the intermittent character of the stream is striking. It would appear that if there was an underground circulation some of the rainfall would be delayed underground to feed the streams a day or two after heavy rain. Mr. F. H. Newell, the hydrographer of the Porto Rican Irrigation Service, stated to me that "the discharge figures show a peculiar condition to exist. They show that almost as much water runs off of the various drainage basins as enters them by rainfall." This does not seem to be an anomaly. It only proves that practically none of the rainfall enters an underground circulation. That rainfall cannot enter a subsurface circulation is not to be wondered at, in view of the character of the soil, which is an extremely unctuous, tenacious, sticky, red, heavy clay. In the interior of the island, where the rainfall is heaviest, this impervious clay is as much as 50 feet thick in places. It adheres to almost vertical slopes despite rains of intense character. Any channels of circulation open at the surface would quickly become sealed by this clay.

The arguments presented above will appear to most readers as quite unnecessary, in view of the fact that meteoric waters to become heated would have to descend beyond a thousand feet or more. The accumulated evidence is now overwhelming in proving that deep rocks are dry rocks (Lindgren, 1913; Kemp, 1903).

TEMPERATURE

The temperature of Coamo Springs is 44° C. Cold meteoric waters would have to descend to over 3000 feet to reach a ground temperature as high as 44° C., unless, perhaps, they came within the influence of volcanic rocks of very recent origin.

LOCATION NEAR A VOLCANIC CENTER

Just south of the Coamo Springs Reservoir dam an old volcanic center is shown in cross-section and in the vicinity of Coamo Springs former post-Eocenic volcanic centers are very common. There is one between the springs and Coamo, another on the Rio des Descalabrados, and to the eastward, in the Jucyes drainage system, are several more volcanic complexes. This spring is thus intimately related to volcanic centers. The close proximity of this spring to young volcanic centers must have a genetic significance. How recently these volcanoes were active is not known. No evidence of the volcanoes cutting the Arecibo rocks has been found. The volcanoes are at least post-Eocene and may perhaps be post-Oligocene.

CONSTANCY OF COMPOSITION

The following table gives the results of four chemical analyses.[7] Number 4 is the analysis made for this study. I am inclined to regard analysis number 3 to be devoid of accuracy and there is much doubt about the other two. Neglecting number 3 and considering only $CaCO_3$, $MgSO_4$ and SiO_2, there seems to be a rather constant value for them all—that is to say, the figures are of the same magnitude. In a limited way analyses numbers 1, 2 and 4 argue for a constant composition over a period of many years.

	I	II	III	IV
HCl	00.84	00.852	.....	.....
H_2SO_4	44.08	36.710	.....	.....
H_2CO_3	27.88	33.433	0.76	.....
NH_4Cl	.....	.....	.....	11.31
Na_2CO_3	.....	.....	2.07	.....
Na_2NO_3	.....	.....	.....	00.38
$NaNO_3$	.....	.....	.....	06.93
Na_2SiO_3	.....	.....	4.79	.....
Na_2SO_4	.....	.....	30.98	.....
$NaCl$	.....	.....	13.60	07.72
KCl	.....	.....	0.02	02.43
$LiCl$	.....	.....	.....	00.34
$CaCO_3$	00.20	00.390	.....	00.01
$CaSO_4$	00.41	00.413	47.12	63.90
$MgCO_3$	20.07	21.460	.....	.....
$MgSO_4$	00.84	00.846	.....	00.63
$FeCO_3$	.....	.....	.....	02.38
Fe_2HCO_3	.....	.....	0.66	00.26
$FeSO_4$	04.59	04.801	.....	.....
SiO_2	01.09	01.095	.....	03.71
	100.00	100.00	100.00	100.00

---

[7] I. J. J. Heller, 1847.

II. Señor Gunenez, 1899. t° 45.3; average temperature of air near springs, 27.3; and constant sulphurous odor; sp. gr., 1.233.

III. 1.6855 grains per mile made at the agricultural station of Mayaguez.

IV. Louis Hernandez, 1916. t° 44° 1.59970 grains per mille.

River waters are solutions of calcium and sodium carbonates and silica. It is an axiomatic fact that river waters reflect the composition of the rock over which they flow, and one should expect spring water which has traveled through such rocks to have a similar composition. These analyses show that this is not the case.

The location of Coamo Springs, their constant flow, the temperature, composition, constancy of their composition and the physical character of the rocks of the older series all argue against the direct meteoric origin for their waters.

POSSIBILITY OF CONNATE, ENTRAPPED AND STRAYED MAGMATIC WATERS

The presence of a new loci of heat, such as an intrusive magma or a volcanic center (and it is to be remembered that a batholith underlies this district), would stimulate entrapped or connate waters and rejuvenate strayed magmatic waters and cause them to rise to the surface and there form springs. Apparently the only way these waters could be distinguished one from another would be by their composition. Lindgren (1913), speaking of connate waters, says that "the presence of bromide is almost characteristic; traces of iodine and boron are often found." These critical elements are lacking in the Coamo Springs waters.

There are some features concerning the composition of the Coamo Springs waters which show their dissimilarity to entrapped meteoric or connate waters. As they issue at the surface they are mostly solutions of calcium sulphate. Their present composition is undoubtedly due to reaction of sulphuric acid with the very calcareous rocks through which the waters pass. Acid waters of meteoric origin are always low in sodium, potassium and lithium, three elements which occur in notable quantities in these waters, and, on the other hand, these alkalies are very common in waters of volcanic origin (Clark, 1916). The ammonia radicle, which is also peculiar to volcanic waters, is strikingly high in the Coamo Springs waters. If the assumption is made that the sulphuric acid has resulted from the oxidation of hydrogen sulphide, then the composition of the Coamo Springs water at depth is an alkaline solution of sodium, potassium, and lithium chlorides, ammonia hydroxide and hydrogen sulphide gas. Such a composition is, indeed, unlike any entrapped meteoric or connate water! The composition indicates that the Coamo Springs waters are neither connate nor entrapped meteoric waters, but it does not disprove them to be entrapped magmatic waters. Moreover, strayed magmatic would have a composition identical with entrapped magmatic waters, or, for that matter, secondary magmatic waters. Strayed magmatic waters or entrapped magmatic waters could be rejuvenated so that they ascended to the surface and there formed springs. The waters of Coamo Springs may have such an origin.

POSSIBILITIES OF SECONDARY AND PRIMARY MAGMATIC WATERS

Two other possibilities of origin that remain to be considered are secondary and primary magmatic waters. Waters contained in rocks invaded by a magma are considered by some writers to be able to enter a magma either by assimilation of the country rock or by diffusion from the country rock into the magma. After the waters had entered the magma their composition would have become changed, so that they could not be distinguished from primary magmatic waters. The problem, then, resolves itself into a consideration of the possibilities of diffusion and of assimilation.

ASSIMILATION

Even the most enthusiastic exponents of magmatic assimilation admit that the process of assimilation does not take place in the zone of flowage, and we need only consider in this zone absorption by diffusion.

DIFFUSION

In order to diffuse, water must be present in the rock adjacent to the magma and it must be available. Rocks in the zone of flowage do not have more than 0.5 per cent by volume of pore space. The pore spaces that do exist are closed and completely separated from one another by crystalline substance. There is absolutely no evidence, experimental or geological, that gases can diffuse through solid crystals. A minute passage must always be present. Granting that a little water exists in these pores (though the experience of deep mines and bore-holes is quite to the contrary), would it in any manner be able to create fractures or develop cleavages through which it could pass to the magma? Of course the water in the pores adjacent to the intrusive magma would be absorbed, but the quantity would be infinitesimal. Adjacent to the magma the temperature is 1000° C. or higher. From the walls of the magma outward the conductivity of the rock is so low that within a few feet the temperature is lowered to 500 degrees, and from that diminishes rapidly outward. There is about the upper surface of the magma a zone 10 feet thick at most which has a temperature sufficient to raise water above its critical point of 364.3° C., and throughout this zone all the water stored in the pores is in the vapor phase. In this state and brought in contact with solutions of minerals composing the magma, water will rapidly diffuse and become incorporated into the magma.

There are two factors which would prevent this diffusion taking place: one is the cubical expansion of the minerals upon heating, and the other is the immense outward pressure of the gases contained within the magma. The minerals of the rocks next to the intruded magma would expand, when heated, in all directions. If the pores were empty they would be closed. If the pores contained water vapor, this vapor would either be compressed or forced to move along some plane of weakness. If the water vapor moved in any direction it would necessarily move outward and away from the magma, because in that direction the temperature would be lower and the cubical expansion less. Any fractures present or separation along cleavage planes would be closed tight and the pressure forcing them tight would be *greatest near the magma* and less far away. Thus the magma in the zone of flowage hermetically seals itself on the outside by a layer of rock, ten feet or more wide, through which gases cannot pass and out of which water vapor, if it must escape, will be compelled to travel away from the magma.

All authorities on igneous rocks, such as A. Harker, A. Lacroix, Joseph P. Iddings, R. A. Daly and numerous others, ascribe to magmas enormous quantities of gases, such as water, carbon dioxide, boron, fluorine, chlorine, and others in lesser amounts. Whether these gases are able to free themselves from the magma in the zone of flowage or not, the tendency is there and the outward pressure of these gases is sufficient if released to drive outward and away from the magma any water which might exist. These gases probably do not escape in the anamorphic zone because of the hermetical zone surrounding the magma, as discussed in the above paragraph. As magmas approach the upper limits of the anamorphic zone and the outward pressure of the dissolved gases becomes greater, due to crystallization, it is probable that these gases may open up veins for themselves, but in so doing the velocity of their outward movement would not permit any water contained in rock pores to diffuse toward the magma.

ASSIMILATION OR DIFFUSION IN KATAMORPHIC ZONE

In the katamorphic zone of the earth's crust, where fractures may exist and pore spaces are larger, cubical expansion of the minerals, due to the heating by the uprising magma, will not be sufficient to form a hermetic shell. Any water which by some unexplained manner may get down a thousand or two thousand feet, if brought in contact with a magma, would diffuse into it. Smaller cavities and fractures close to the magma will be closed, but larger fractures will be filled by injected masses of rock. The peripheral portions of these injected igneous rocks will allow diffusion into them of water vapor, but the area of the terminal portions exposed to diffusion will be small and allow of no contribution directly to the magma. If these injected bodies succeed in completely surrounding a block of rock and this block sinks into the magma, because of greater relative density, or if a slab of rock is loosened by shattering, any water contained will be incorporated.

The speed of marginal shattering or block dissection will be a slow process and will always be preceded by an outward radiation of heat from the magma. The heat will convert the water to steam, which will move in the direction of least resistance. The effect will be like that of the emanations from the magma, for the steam will drive any water contained in the rock outward and away from the magma. This steam will not be able to move toward the magma, because of cubical expansion close to it, because of the outward traveling injected bodies, and because of the emanations. Before, therefore, a block could be assimilated, all the water contained would probably be driven out of it. As the intrusive works its way into the fracture zone, the indigenous gases will escape outward. They will drive all other gases before them. Their outward velocity is great and penetration power most complete, which is illustrated by the way in which these gases follow out and open up the cleavage planes of calcite grains of a limestone in the phenomena of contact metamorphism. The waters which the outward moving gases meet with are dissolved, but the speed of diffusion in the gaseous solution is undoubtedly slower than the speed of the outward moving gases, and all waters in the invaded rocks would be carried along the crest of the first wave of emanations. The upward movement of the magma is slow and this process will act continuously until all the gases are spent. Apparently, then, only an unimportant fraction of water contained in the invaded rocks could diffuse into a magma and we must conclude that the probabilities are highly in favor of the theory that the waters of the Coamo Springs are appearing at the surface for the first time in their history.

MINERAL RESOURCES

GENERAL CONSIDERATIONS

The possibilities of metal mining in Porto Rico are discouraging for several reasons: One is the absence of cheap power. Coal and oil must be imported and water-power sites are limited. Another is due to the fact that the ore could not be smelted locally; hence only high-grade ore could be shipped. This would mean the building of railroads on the island and long ocean transportation. The few railroads built on the flat coastal plains have cost between $5,000 and $10,000 per mile. As the mountainous interior is extremely rugged and broken, railroads, where they could be built, would have to rise on steep grades and make very sharp turns. In many places railways are practically impossible and long, expensive aërial tramways would be the only means of transportation. An ore deposit would need to be very rich and large to warrant exploitation under the above-mentioned difficulties.

The island of Porto Rico has been explored for centuries, but up to date not a single paying mine has been developed. No large area contains a more dense population. Nearly every nook and corner has been observed, yet no ore deposit of importance has been discovered. Despite popular legend, there is no evidence that the early Spaniards, though they sought long and zealously, ever found a deposit which could be worked even with slave labor. For centuries the Spaniards and later the ever enthusiastic Yankee prospector searched for ores. Nevertheless, the few prospects opened have never developed into mines.

METALLIC MINERALS

In the Coamo-Guayama district near Barrio del Carmen several prospects have been opened, which I have had opportunity to examine. The character of the larger one, situated just south of Carmen, will be described (Fig. 50).

Several openings have been made in a hill composed almost entirely of a conglomerate with a tuffaceous matrix. The workings follow mineralized crush zones and true veins, and are extensive enough to show the general geological relations. Conglomerate is cut by an intrusion which varies in composition from an augite to a feldspathic andesite. The conglomerate is found in the main drift and the first lateral; it is also found in the various prospect pits on this hill and in the pits north and west of Carmen. The intrusive rock appears in the major part of the workings and a dike cuts the first 20 feet of the first lateral. Mineralized faults of small displacement are common in the andesite and are accompanied by a green andesite gouge, which may be a few inches to two feet thick. The andesite is highly fractured, which may have been due to cooling or to resurgent movements of the subjacent liquid portions after the peripheral portions have solidified, or to tectonic movements. Whatever the cause, the fracturing took place while the magma was still giving off emanations, for the numerous small fractures have a calcite filling and into some of the larger veins pyrite came and filled the central portions. The andesite is incrusted by calcite at its contact with the country rock, and apparently at the time of the intrusion of the andesite $CaCO_3$ bearing waters were given off in great quantity, some of which followed the outer wall of the andesite and precipitated calcite, while others worked up through the fractures and faults and formed calcite veins.

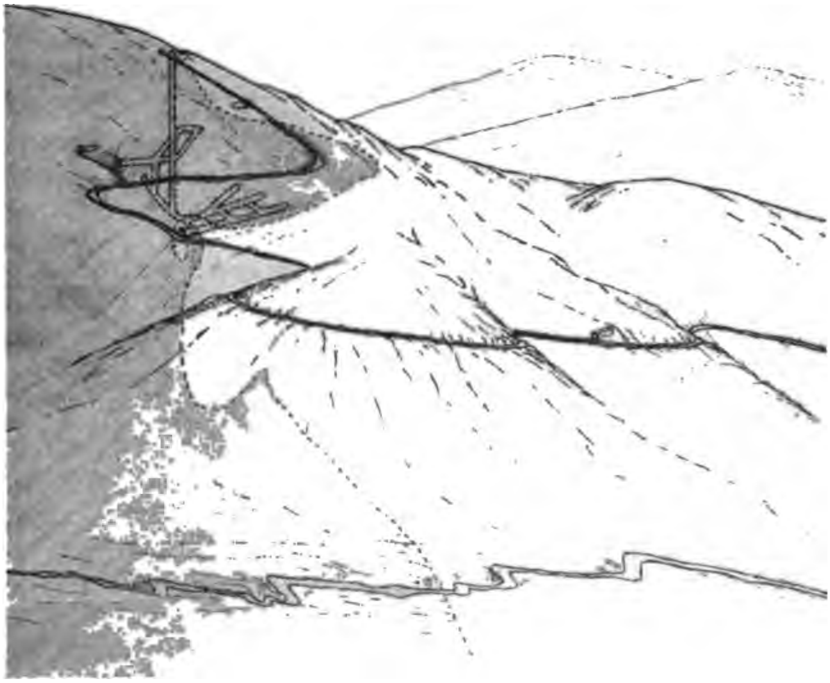

FIG. 50.—*Barrio del Carmen Prospect*

Darker shade indicates an andesite intrusion. Medium shade indicates the tuffaceous conglomerate country rock.

True veins occur, which are crustified and show several generations of quartz deposition. The prospect pits north and west of Carmen open up quartz veins of identical character. Near each, andesitic rock occurs, to which the veins are undoubtedly related. The quartz veins contain pyrite and galena; the succession, which can be plainly made out, is quartz or galena, pyrite and calcite. Not all of the quartz veins are mineralized, for in some veins pyrite was developed first and in others galena. Where galena was formed first, pyrite always followed. Those veins which leave the andesite and penetrate the country rock always show a preponderance of pyrite over galena. Apparently, then, pyrite was the more mobile of the minerals and traveled farthest.

Since the galena is genetically related to the andesite and is the least mobile mineral, it should increase with depth. Considering the difficult transportation problems, the veins of galena exposed in the present prospect make it unworkable unless the galena is rich in silver, which as far as I know is not the case. Much of the present workings have followed slips and gouges and not the true veins. If, in all the exploratory work, the galena-bearing veins had been followed in depth and the slips and seams neglected, the presence or absence of galena in paying quantities would have been completely demonstrated.

COAL

A few coal beds have been reported. One near San Sebastian and another near Juana Dias were examined and in each case the "bed" proved to be merely a thin seam of highly marcasitic low-grade bituminous or lignitic coal. In the Coamo-Guayama district one small seam was observed south of Cayey near the crest of the Sierra de Cayey Mountains.

OIL SHALES AND PETROLEUM

An investigation was made of the oil shale and petroleum possibilities of Porto Rico. Shales were gathered from many localities in Porto Rico which were reported to carry oil or were considered by the writer to have oil possibilities. The results of many analyses of the shales collected were all negative. Detailed study of the structure of the older series was impossible in the limited time devoted to study. In most places, however, it is apparent that the strata have been folded to too high angles and eroded too deeply to preserve intact an oil reservoir which may have existed. There are a few localities, however, where the beds show the gentle folds suitable for oil storage, as, for instance, between Cidra and Cayey. Perhaps a more careful study would reveal structures worth testing for oil.

ROAD-METAL

Limestone outcrops are numerous, most of which are suitable for road-metal. Along the San Juan to Ponce Road outcrops were noted at the following places:

Kilometer	.9
Kilometer	55.8
Kilometer	61.1
Kilometer	61.4
Kilometer	67.0
Kilometer	73.2
Kilometer	78.2
Kilometer	84.0
Kilometer	85.1
Kilometer	87.7
Kilometer	90.9
Kilometer	94.2
Kilometer	99.5
Kilometer	100.3
Kilometer	104.1
Kilometer	105.3
Kilometer	106.6
Kilometer	107.5
Kilometer	108.2
Kilometer	111.9

West of Cidra two good limestone outcrops exist. Limestone is almost absent from the Cayey to Guayama Road, but andesite intrusives occur almost continuously. The Aibonito to Barranquitas Road shows many outcrops of silicified shales suitable for road-metal. The limestone of the Coamo Springs Range serves as a convenient source of suitable rock for the Coast Road.

SALT

Two salt pans exist just southeast of Salinas. About 30,000 pounds of salt have been obtained from these pans by evaporation of sea water.

CLAYS

The surface of the mountainous interior of Porto Rico is universally covered by a heavy, sticky, ferruginous clay akin to the gumbo found in the United States. This clay is too plastic and too ferruginous to be used for structural brick, paving brick or sewer pipe unless properly mixed with shales and carefully burnt, and fuel is too expensive to make elaborate burning feasible. Such clays, however, are suitable for low-grade tile and pottery. Some building bricks have been made in Porto Rico. In the Coamo-Guayama district low-grade red bricks were made near the following places:

Coamo	20,700 brick, valued at	$140
Guayama	250,000 brick, valued at	$2,000
Santa Isabel	50,000 brick, valued at	$300

The bricks manufactured are extremely friable, as would be expected, considering the primitive methods of manufacture employed. The clay is mixed and ground in a circular pit around which a wagon wheel is pulled by a horse. The wheel is attached to a long beam which is fixed to a pole in the center of the pit. The prepared clay is hand-molded and dried in the sun, after which the green brick are built into a rectangular kiln. Charcoal is used to burn the brick.

LIME

Stone suitable for lime burning is probably not present in this district. As shown in the earlier part of this report, all the limestones are high in tuffaceous materials, which makes them unsuitable for a lime as pure as required by the sugar industry.

NATURAL CEMENT

The presence of the tuff, however, makes the limestones of a composition required for natural cements. This fact was demonstrated by the Central Aguirre. This Sugar Company burnt some of the limestones in the Aguirre Hills hoping to prepare a pure lime, but the product they obtained was a cement.

STRUCTURAL LIMESTONE

Limestone is the best tropical building stone. The heavy vegetation keeps the carbon dioxide content of the rain and ground water so low that solution has but little influence. This is shown by the San Juan fortress and castle, which, after standing for centuries, are as good and solid as the day they were built. The best limestone in the Coamo-Guayama district is that of the Coamo Springs Range, which offers an inexhaustible supply. This limestone in most places is heavy bedded, solid and uniform. West of kilometer 108, on the Military Road, a quarry is being worked in a desultory fashion. The limestone is not only easily quarried, but is accessible from the Coast Road along nearly the whole of the district.

THERMAL SPRINGS

Three thermal springs exist in Porto Rico. The Quintana Spring is located in a subsequent valley, lying north of Ponce, just at the foot of the mountainous interior, where the rocks in the immediate vicinity indicate the former loci of volcanoes. The Coamo Spring has been described. North of Arroyo and situated far out in the coastal plain is the Virella

Spring. The following analyses of the waters of the above springs were made for this report by Mr. Louis Hernandez, of the Porto Rican Service of Sanitation:

Quantitative Analysis

	COAMO. Parts per million.	VIRELLA. Parts per million.	QUINTANA. Parts per million.	Amount of water used. (c. c.)
Nitrites	.002	.00	.004	100
Nitrates	.03	.02	.02	100
Free ammonia	.048	.0432	.012	.....
Albuminoid ammonia	.072	.048	.012	.....
Total ammonia	.12	.0912	.024	1000
Potassium	.0184	.0697	.012	500
Sodium	.14908	.819	.26517	500
Lithium	.003861	.00287	.00389	10000
Sulphates	.60892	.4598	.125	1000
Magnesium	.00409	.0012	.0437	1000
Calcium	.41976	1.6877	.0846	1000
Chlorine	.13184	1.35796	.16269	100
Iron	......	....	.002	1000
Iron and aluminum	.0233	....	......	1000
Silicon dioxide	.0596	.3678	.037	1000
Carbonates as CO_3	.01787	1.06577	.00178	100
Bicarbonates as HCO_3	.00302	....	......	100
Ferric oxide	......	.00402	......	.....
	1.60374	5.84702	.78583	

	COAMO.	VIRELLA.	QUINTANA.
Sodium nitrite	.006	....	.00643
Sodium nitrate	.1108	.0739	.0729
Ammonium chloride	.1809	.1374	.03615
Lithium chloride	.00542	.00343	.00467
Potassium chloride	.0389	.1469	.025
Sodium chloride	.12346	2.1991	.3476
Magnesium sulphate	.01023	.004	.1094
Calcium sulphate	1.02254	1.1088	.1439
Ferric carbonate	.03797	.00759	.00378
Ferric bicarbonate	.00418	....	......
Silicon dioxide	.0593	.3678	.037
Calcium carbonate	......	1.7721	......
	1.59970	5.82102	.78683
Total solids	1.6048	5.8242	.7914

Qualitative Analysis

	COAMO.	VIRELLA.	QUINTANA.
Bromine	Negative.	Negative.	Negative.
Iodine	Negative.	Negative.	Negative.
Hydrogen sulphide	Negative.	Negative.	Negative.
Carbonic anhydride (Free)	Negative.	Negative.	Negative.
Free sulphurous anhydride	Negative.	Negative.	Negative.
Phosphoric anhydride	Negative.	Negative.	Negative.
Boric acid	Negative.	Negative.	Negative.
Lithium (spectroscopically)	Positive.	Positive.	Positive.
Specific gravity	1.003	1.006	1.004
Temperature	44° C.	30° C.	34° C.

Coamo Water: No reaction on litmus; alkaline to phenolphthalein, but on boiling the color disappeared.
Virella Water: Alkaline to litmus and phenolphthalein.
Quintana Water: Neutral to litmus, but alkaline to phenolphthalein.

The high sodium chloride content of the Virella waters is probably due to wind-carried salt spray of the near-by coast and to the fact that the waters issue through the recent coastal plain deposits, which have not as yet been completely freed of their connate sodium chloride. The high magnesium chloride content of the Quintama Springs makes their waters unsuited for drinking purposes. The waters of the Coamo Springs are good to drink and a trade in bottled waters should be developed. The temperature of the Quintama and Coamo Springs has encouraged their owners to build comfortable bathing pavilions, which will attract more and more tourists as their fame spreads abroad.

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GEOLOGIC MAP

EXPLANATION

Recent–Santa Isabel formation; mostly alluvia.

Oligocene–Arecibo formation; mostly limestone.

Eocene	Rio Descalabrado series; a thick series of shales with a little limestone and chert. Coamo Springs series; a heavy bedded limestone. Rio Jueyes formation; a complex series, mostly limestone, but with much shale, some tuffs and conglomerates.
Comanche to Cretacic	Guayma series; a complex series, mostly of shale, but with much chert, some tuff, limestone and conglomerate. Sierra de Cayey series; mostly conglomerate, with a little tuff and some shale.
Comanche	Barranquitas–Cayey series; mostly shales, with much limestone and a little tuff. Rio de la Plata series; mostly tuff, with a few agglomerates, shales and limestones.

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GEOLOGY OF THE PONCE DISTRICT, PORTO RICO

BY GRAHAM JOHN MITCHELL

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INTRODUCTION

Nature of Investigation

A geological study of the Ponce District, an area of about 850 square miles, in the southwest corner of the island, was undertaken with the expectation that in this less humid section some points in the geology—for example, the structure and age of the Older Series and the question of recent changes of level—might be determined. The relation of this area to other parts of Porto Rico may be seen by reference to the Outline Map.[1]

The field-work occupied the period from June 1 to September 8, 1917, and the report was completed in the Geological Laboratory of Columbia University during the succeeding winter. Field-work was carried on from the principal cities and towns as headquarters, saddle-horses being the chief means of transportation. The formations along all roads, numerous trails, and many stream courses were studied, and it was along such routes that the best exposures and decipherable structures were found, especially in the Cretaceous rocks. Seven main traverses were made from north to south, with many detours into adjoining territory, thus making it possible to examine all formations of any consequence.

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[1] Scientific Survey of Porto Rico and the Virgin Islands, I, pt. 1, p. 26.

Geological and Topographical Map

The base map for the region was compiled from maps of the United States Coast and Geodetic Survey and of the Insular Government, supplemented by the writer's field-notes. The scale used, 1: 50,000, or approximately one and a quarter inches to one mile, makes it possible to show areally small intrusive bodies which could not have been represented on the available smaller-scale maps. The topography is generalized, but care has been taken to depict the surface features in as much detail as time would allow.

Routes of Travel

On the Geological Map an attempt has been made to differentiate the first-class macadam roads from those of second grade. All important trails are also shown on this map, but the innumerable local paths of the natives have been omitted.

Climate and Vegetation

The climate is tropical, but modified by the trade winds and by the land and sea breezes. The district as a whole has less rainfall than other parts of Porto Rico. In fact, the extreme southwest corner borders on aridity. The mountains along the northern boundary of the district receive a copious supply of moisture from the sudden downpours, which were observed to be a daily event during the period spent in the district.

Tropical vegetation is rank in most of the higher mountains. It forms a tangled mass, through which it is often necessary to chop one's way unless roadways or streams are followed. However, all the mountain slopes are not so heavily coated with plant growth, some being comparatively barren; for example, the serpentine ridges north of Sabana Grande and some of the hills of Tertiary limestone along the south coast.

Acknowledgments

The many courtesies extended by residents throughout the island and the material assistance given by not a few of its people not only added pleasure and comfort throughout the work, but were in a measure responsible for the satisfactory completion of the field investigation.

Among those who rendered special service were Col. George R. Shanton, Chief of Insular Police. Governor Yager's suggestions of a general nature and his assistance in getting the field-work started were highly appreciated. Dr. Lippitt, of the Bureau of Sanitation, gave information concerning sanitary conditions and also furnished letters to residents in the district. To Señor Manuel Gonzales, of Salinas, the writer is indebted for the loan of saddle-horses, the securing of which made it possible to cover the area in much greater detail than could otherwise have been done. Deputy United States Marshal George Trautman, of Ponce, spent one day in the field with the writer, pointing out features of interest in the vicinity of the manganese deposit north of Juana Diaz. The efficient service of Señor Fernando Oliver, Jr., as interpreter was a considerable aid in the field-work.

The field-work and preparation of the report have been under the general direction of Dr. Charles P. Berkey, whose interest has been a source of inspiration. Dr. Amadeus W. Grabau has made valuable suggestions in stratigraphical and paleontological matters, as has also Dr. J. J. Galloway.

Dr. T. W. Stanton, of the United States Geological Survey, determined the *Radiolites* sp. and *Actaeonella* sp., and thus made it possible to place the age of the oldest rocks as Upper Cretaceous. Dr. Robert Tracy Jackson identified the *Clypeaster rosaceus* and the new species *Hemiaster berkeyi*. He has also kindly furnished a description for the latter. Lastly, the writer wishes to express his acknowledgments to the New York Academy of Sciences, which institution made it possible to carry on the investigation.

PHYSIOGRAPHY

Introductory Statement

The broader relief features of the Ponce District may be grouped as follows:

(1) A complex mountainous area, the westward continuation of the central Cordillera, which is characterized by angular ridges and deep, narrow valleys cut several hundred feet below the general level of the mountain surface, the altitude of which rises to over 3600 feet in the highest peaks, in the region to the southwest of Adjuntas. These mountains stand on the north side of the district, and their southerly and westerly slopes stretch toward the coast with more or less uniformity and pass beneath the remnants of Tertiary coastal plain sediments which border the south coast. The southwestward continuation of this "old land" surface is broken by two conspicuous, broad valleys, one extending from Yauco on the east to Boqueron, on the west, and the other occupy-

ing the triangular lowland from San German to Cabo Rojo. The most rugged section extends along the northern side of the region from the eastern boundary, east of Villalba, to the vicinity of Maricao, the hills becoming lower and the valleys broader as one approaches the south and west coasts.

(2) A much-dissected coastal plain of Tertiary sediments, which at one time lapped over the eroded surface of these complex mountains, but is now faulted down against the older rocks and forms a border along the south coast. These coastal-plain deposits are cut into isolated remnants by streams flowing through to the Caribbean Sea.

(3) Lowland areas, some quite extensive, occupy present and former river valleys and stretch along the coast in broad, gently seaward sloping plains, called playas. The most striking of such lowlands are the valleys between Yauco and Boqueron and the valley of the Guanajibo River. The most extensive playas are Ponce, Guayanilla, Cape Rojo and Mayaguez.

In the following pages the physiographic details of these broader relief features will be presented, together with a discussion of minor surface configurations.

COMPLEX MOUNTAINS

EXTENT

The complex mountains occupy over three-fourths of the region. They extend beyond the district boundaries on the east and north and reach the sea on the west. The southern limit is marked by the fault separating the Tertiary and Upper Cretaceous rocks.

RELIEF

The relief is rugged along the northern border, whereas the ridges become more rounded and the valleys broader as the southern and western boundaries are approached. When viewed from the hills south of Yauco, the upland surface has a gradual slope southwestward from the main drainage divide north of Yauco to the low hills of the west coast, extending from Mayaguez on the north to Cape Rojo Playa (Fig. 1). On closer inspection the intensive dissection which progresses daily under the tropical showers greatly impresses the observer. The steep slopes of the higher mountains turn the waters into narrow gorges, where, after heavy storms, raging torrents are ever deepening and widening their valleys. The heavy coat of tropical vegetation checks the rapid run-off, but the impervious character of the surface soil facilitates it. Such valleys as the upper Rio Yauco, Rosario, Guayanilla, Tallaboa, Canas Bucana, Guanajibo, Guaba and Preito are typical of this mountain region.

The evidence of peneplanation of the older rocks before the deposition of the Tertiary is not so conclusive as on the north side of the island. There the old erosion surface, developed at the close of the Cretaceous and early Eocene, is plainly visible (Berkey, 1915, p. 41). In the Ponce District the only locality where this old erosion surface appears to be preserved is on the "Mesas" near Mayaguez.

RELATION OF TOPOGRAPHY TO ROCKS AND ROCK STRUCTURE

The influence which different rocks and rock structures have exerted in the development of surface features is shown in many instances. The formations most resistant to weathering are the San German and Guayabal limestones, the igneous intrusives, and the highly indurated tuff. One need only see the white ridges of the San German and Guayabal formations, surrounded by lower-lying areas of tuff and shale, to

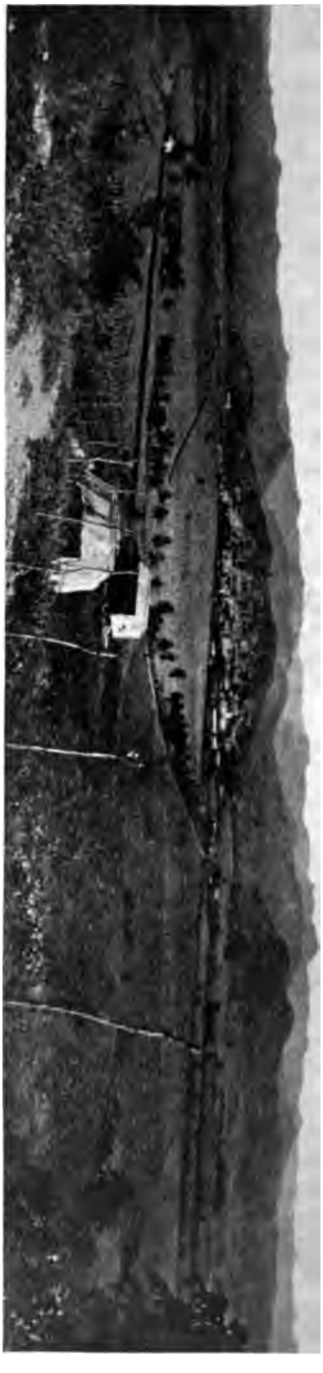


FIG. 1.—*Portion of Complex mountain province as seen from the Tertiary hills south of Yauco.* Yauco nestles on the hillside with the Rio Yauco (Lowland) Valley in the foreground.

realize the importance of these highly calcareous beds in the physiography of Porto Rico.

The tuff and ashy shale weather readily, although it must be remembered that the more strongly indurated tuffs are among the rocks most resistant to erosion. The ashy shales are easily disrupted and cut away, and it is along belts of such material that the head-waters of some of the streams are forming deep valleys with sharp ridges between. Shale higher in lime content, as, for example, that at Ensenada, is a good ridge-maker. Reference to the geological and topographical map brings out the fact that the largest valleys, as, for example, Yauco-Boqueron and Guanajibo, are formed principally on tuff. A factor which has accelerated the erosion of tuff in the southwestern part of the district is exfoliation. By this process numerous tuff exposures are undergoing disintegration.

The structural attitude of such rocks as the San German and Guayabal limestone is in part responsible for some of the most striking surface features in the region. The tilted position of these strata, with more easily eroded material both below and above, has given rise to ridges like the one to the east of Guayabal reservoir and those forming the south face of Yauco-Boqueron and Guanajibo valleys.

The development of subsequent valleys by headward erosion along weaker rock-belts can be seen north of Yauco, where the head-waters of the Guayanilla are working back along belts of tuff and shale. Other smaller, subsequent valleys are found along the south coast, as, for example, the one at Ensenada and the extensive lowland between Yauco and Boqueron and the valley along the Guanajibo.

DRAINAGE

The present drainage is divided among fifteen main streams and their tributaries. The area east of a north-south line drawn approximately through Yauco is drained by eight principal rivers, among which are the Jacaguas, Tallaboa, Guayanilla, Bucana, Inabon, Portugues, Canas, Yauco and Susua. These streams, whose head-waters are in the mountains to the north, cross the geological structure approximately at right angles in the lower three-fourths of their course to the Caribbean Sea. Each has cut a deep valley along its upper course, but on reaching the coastal plain the breadth of this valley is considerably increased, and in instances, like the Ponce Playa, the confines of individual streams are lost in the flat coastal lowland. The course of the drainage across the structure supports the idea of superposition from a former more extensive Tertiary coastal plain, and, as will be shown later, this has probably been the case.

The principal westward-flowing streams are the Guanajibo, with its tributaries, the Viejo, Rosario, Hoconuco, Cain, Flores and Mayaguez. The history of the Guanajibo is of special interest, due to its capture of streams to the east of San German. These streams formerly flowed south through the Yauco-Boqueron Valley to Guanica Bay. The original Guanajibo, which drained westward from San German, had a shorter course to the sea than the streams of the Yauco-Boqueron Valley. As a consequence, it pushed back its head-waters, which were then west of San German, to a point east of the city. The Cain and Flores, with their branches, were then following a longer southerly route and developing the Yauco-Boqueron lowland. With the eastward advance of the Guanajibo, this southward drainage was captured and diverted to the west. The water gaps in the hills southeast of San German strongly support this conclusion. Stream gravels are present in some of these gaps.

The north-flowing streams are Mayaguecillo, Guaba, Bucarabones, Prieto, and Blanco, all of which pass into the adjoining area, studied in detail by Mr. Bela Hubbard. These streams are working mostly in shale and tuff and are rapidly cutting back their valley heads along the main drainage divide.

TERRACES

The only terraces found along streams are those formed by the entrenching of formerly deposited river alluvium. Such terraces are more strongly developed along the lower stream courses, but a few examples are found bordering the wider sections of the upper stream valleys. It is my belief that these terraces are connected with the recent changes of level which have affected Porto Rico. A wave-cut terrace has been formed on the Cretaceous rocks making up the point just south of the Reform School, southwest of Mayaguez. The details of the terraces due to wave action will be found in the section describing the Historical Geology.

TERTIARY COASTAL PLAIN

EXTENT

What remains of the Tertiary coastal plain along the south coast of Porto Rico extends from a point a short distance east of Juana Diaz to Cape Rojo and Point Aguila, in the southwest corner of the island. This physiographic province is not continuous, but is cut into isolated areas by the rivers traversing southward. The largest portion is confined to the vicinity of Ponce and continues west to the region of Ensenada. The exposures at Cape Rojo and Point Aguila are small and underlie the San Juan formation at the former locality. The northern boundary is determined by the fault, which is discussed later under structure.

RELIEF

In contrast with the complex mountains, the coastal plain has a much smoother aspect. Viewed from a distance, it is seen to approach, with a gentle south slope, the "old land" on the north. The boundary between these two physiographic units is in most cases characterized by an erosion scarp forming the south wall of the discontinuous fault-line valley developed along the fault zone between the Tertiary and Cretaceous areas. The surface is diversified by stream valleys both across and parallel to the strike. The greatest altitude reached is a little over 900 feet, in the area southeast of Peñuelas, and the slope is southward and southwestward from this point.

RELATION OF TOPOGRAPHY TO ROCKS AND ROCK STRUCTURE

The soft, chalky character of much of the strata making up the coastal plain offers little resistance to erosion. Streams have slight difficulty in developing their valleys, and would cut them much faster were it not for the fact that the rainfall in this part of the island is much less than in other sections of Porto Rico where the Tertiary is found. Harder strata, sometimes a foot or more in thickness, have protected the underlying material, thus producing low cliffs. This, however, is a minor feature. On the north coast shaly and harder strata have been in part responsible for the haystack topography (Berkey, 1915, p. 51). None of this type of topography was seen in the Ponce District.

The ease with which water enters and dissolves the limestone is responsible for the pitting of the surface with depressions having no apparent outlet. Such sinks are to be seen in the region of kilometer 67.0 along the Ponce-Peñuelas road. These depressions are very inferior to similar occurrences on the north side of Porto Rico.

DRAINAGE

The principal drainage consists of the main streams, which rise in the mountains to the north and traverse the coastal plain through open valleys bordered by low hills. All of these streams lie to the east of Ensenada, the Tertiary area to the west being void of any but intermittent streamlets. Among even the larger rivers, few maintain a constant flow to the sea. Observations during the three months spent in the district proved most of them to be of torrential habit, at times filled to overflowing, then receding again to dry channels. The amount of rock waste which such torrents transport is large. Boulders several feet in diameter can be found in stream channels during low water.

Gaps in which water-worn gravel is found occur east of Ponce, in the Tertiary limestone ridge along the south face of the lowland between Ponce and Juana Diaz. The largest of these gaps is just southeast of kilometer 127.0, on the road from Ponce to Juana Diaz. Formerly the Bucana River occupied this depression, but has since taken a westward course to the Ponce Playa. Other gaps notch the Tertiary ridges, but conclusive evidence of stream capture in such instances was not found.

TERRACES

Both stream- and wave-cut terraces are present. The former are similar to those described under the complex mountain area, but are more extensive; the latter are represented by old marine levels along the south coast. The stream terraces are best seen along the Bucana River north of the military road from Ponce to Juana Diaz. The successive levels at this locality have cut through alluvium to underlying rock.

Wave-cut benches on the Tertiary along the south coast of the district are well developed on the headlands at the mouth of Guanica Bay and a short distance both east and west of this point. The elevation of these levels ranges from 10 to 200 feet and bevels the south-dipping Tertiary limestone beds. In some instances cliffs at the inner margin are partially preserved, but in most cases the soft character of the chalky limestone has prevented their preservation.

There has been some difference of opinion, among those who have studied the district, concerning the question of recent changes of sea-level in Porto Rico. In the following pages the evidence secured by the writer in the survey of the Ponce District will be presented. The localities listed range from east to west and include terraces cut on the Cretaceous, as well as on the Tertiary rocks. Berkey (1915, p. 48) describes terraces in the region near Guayama, on the south coast, which he attributes to wave action. Their levels range from 100 to 200 feet. The evidences of recent changes of level, together with conclusions on the question, are as follows:

(1) One-half mile southwest of Juana Diaz, on the north bank of the Jacaguas River, the folded Tertiary beds are beveled and a deposit of silt, sand and gravel 2 to 12 feet thick covers the surface. In this surface

covering, at an elevation of 130 feet, are found numerous *Strombus pugilis.*

(2) At kilometer 72.5, on the Ponce-Peñuelas road, recent marine fossils are found in finely stratified material of estuarine character. In this deposit a layer of black mud averaging one foot in thickness occurs at a depth of from 2 to 5 feet below the surface. In this black mud are found *Strombus pugilis, Lucina jamaicensis, Lucina tigrina, Arca tuberculosa,* and *Byssoarca ziebra.* These fossils are also found in other parts of this deposit, the elevation of which is 180 feet.

(3) Across the west branch of the Cañas River, just east of the above locality, the same species of fossils as occur at (2) are found in the stratified sands and gravels at a depth of 3½ feet below the surface and an elevation of 160 feet.

(4) Southeast of Yauco, 1¼ miles, in the Rio Yauco Valley, abundant fossils are found in the surface covering of the river valley at an elevation of 150 feet. The fossils include *Murex elongatus, Arca rhombea, Lucina tigrina, Arca tuberculosa, Turritella imbricata, Pecten nucleus, Venus cancellata, Ostrea virginica, Pterna* sp.

(5) East of Yauco, one-eighth of a mile, the pre-Tertiary rocks are truncated, and in the gravel and sand which cap the beveled strata are found *Arca tuberculosa* and *Lucina tigrina,* occurring at depths of 1 to 2 feet below the surface. The elevation at this point is 200 feet.

(6) On the coast southeast of Yauco a terrace surface bevels the Tertiary limestone at an elevation of 60 to 160 feet, the inner margin being marked in places by a cliff. The following fossils are found on this surface: *Strombus acciptrinua, Fissurella nodosa, Arca rhombea,* and *Turbo pica.*

(7) Just north of the lighthouse at Guanica the Tertiary limestone is beveled by terraces at levels of 10, 50, and 150 feet, and in the surface soil on the two upper terraces are found *Arca tuberculosa, Lucina tigrina* and *Turbo pica.* At the ten-foot level large numbers of these fossils are found in the lime sand and silt which coat this terrace.

(8) East of Guanica one-eighth of a mile, on the east side of the Susua Valley, a terrace at an elevation of 50 feet contains in the surface layers the forms *Lucina jamaicensis, Arca tuberculosa,* and *Turbo pica.*

(9) At the town of Ensenada (Central Guanica) the shale is truncated and a deposit of shells, mud, silt and sand covers the surface to a maximum depth of 5 feet. The fossils occur at an elevation of 45 feet and include the following: *Murex elongatus, Manicina* sp., *Venus cancellata,* Operculum of *Turbo, Arca rhombea, Cerrethium litteratum, Ostrea virginica, Arca tuberculosa, Byssoarca ziebra.*

(10) On the south side of Pardas Bay, south of Ensenada, the Tertiary limestone is again terraced at an elevation of 65 to 100 feet, and the fossils *Arca rhombea, Arca tuberculosa* and *Lucina jamaicensis* are found buried in the soil of the surface.

(11) On Cape Rojo, in the southwest corner of Porto Rico, the San Juan formation, which has been interpreted by Berkey as a lime sand of dune origin, is found at an elevation of 75 feet, overlain by 3 feet of conglomerate consisting of well-rounded pebbles. In the San Juan formation occurs a *Conus* sp. very close to the recent form *Conus portoricanus.*

(12) On Aguilla Point, the extreme southwestern portion of the island, recent gastropod shells are found in consolidated gravels at an elevation of 11 feet. At an elevation of 25 feet they occur on the beveled surfaces of the rocks which make up this point.

(13) Three and three-quarters miles southwest of Mayaguez, on the coast near the Reform School, a terrace is cut on the Cretaceous rocks at an elevation of 50 feet. The inner margin is marked by a cliff, and the following fossils are found in the surface soil: *Arca tuberculosa, Venus cancellata, Lucina jamaicensis.*

The argument has been advanced by Lobeck that where recent fossils have been found in Porto Rico they are associated with Indian mounds. Such an interpretation, however, could not explain the existence of shells buried in stratified material of estuarine character at depths of from 2 to 5 feet. Furthermore, although in each of the thirteen localities cited above the writer made careful search for artifacts, in no instance was evidence found to substantiate the Indian-mound theory.

Based upon the evidence presented in the thirteen above-mentioned cases, the writer draws the following conclusions: With the recent changes of level the old river valleys were embayed, allowing the sea to enter with its marine fauna and to lay down deposits of sand, silt and mud. That these deposits—for example, at localities Nos. 1, 2, 3, 4, 5, 8 and 9—were laid down in Quaternary time is evidenced by the fact that over 95 per cent of the fossils are of the same species as those living at the present time in the adjacent sea. In the remaining instances, Nos. 6, 7, 10, 11, 12 and 13, the truncation of the underlying beds of limestone and other formations along the south and west coasts and the presence of cliffs at the inner margins of some of these terraces, together with the recent fossils found on the surface, are facts hard to explain if they are not connected with the work of the sea.

In considering the question as to which has been the shifting element, the land or the sea, the evidence indicates a change in the elevation of the land. If the sea-level had varied and the land had remained stationary, one should find some uniformity in the terrace levels at particular stages. Such uniformity does not exist. In summing up the conclusions the writer feels justified in stating that there has been differential uplift of the land in Porto Rico in recent time, with a maximum change of at least 200 feet.

LOWLANDS

VALLEYS

Two of the most interesting valleys from a physiographic standpoint are the lowlands occupied by the Guanajibo River, especially the triangular portion between San German, Cabo Rojo and Hormigueros, and the broad stretch of nearly level area between Yauco and Boqueron. The development of the former has been at the expense of the latter.

The Guanajibo River occupies a valley, the head of which lies just east of Sabana Grande. The lowland extends westward along the river, and narrows north of San German to less than one-quarter of a mile. A short distance westward it again widens into the triangular area already described. In the northwest corner of this triangle the valley is once more reduced in width and finally opens out into the Mayaguez Playa. The history of the development of this valley is intimately associated with the rocks, rock structure, and drainage of the region. The underlying formation is chiefly tuff, with some shale. The strike is in general parallel to the length of the valley. Berkey has suggested that the triangular portion already mentioned is related to an old volcanic vent, where the extremely broken and easily disintegrated rock material would allow rapid removal by streams and at the same time account for the shape of the depression. The evidence in the case is not clear, because a deposit of alluvium covers the valley floor to such an extent that only scattered exposures of the underlying formations could be examined. Where such exposures were seen they were found to be tuff like that exposed in the hills to the east and west. The narrow portions of the valley, for example, north of San German are bordered on the south by peridotite, largely changed to serpentine. In the case of the depression now occupied by the Guayabal reservoir, north of Juana Diaz, the evidence of a former center of volcanic eruption is clear (Berkey, 1915, p. 37). The extremely broken and heterogeneous mixture of volcanic fragmental material has offered comparatively little resistance to erosion, with the result that a similar but much smaller lowland than the one along the Guanajibo has been formed. Whether or not the lowland along the Guanajibo has a similar history to the one marking the site of the Guayabal reservoir, I was not able to determine from the evidence presented. However, it was found that the more easily eroded rocks underlie this area, the chief eroding agents being the Guanajibo and its western branch, the Viejo River. Another factor in controlling the shape and extent of this lowland is the San German limestone, which forms the south wall and has developed an erosion scarp with east-west trend along the southern boundary. The relation of the history of the Guanajibo Valley to that of the Yauco-Boqueron lowland is closely associated with drainage modifications of the Guanajibo. By working eastward, the head-waters of this stream captured those which formerly flowed south through the Yauco-Boqueron depression to Guanica Bay. Further details of this capture will be found in the discussion of this latter valley.

The Yauco-Boqueron Valley, a name suggested by Lobeck, extends from Yauco on the east to Boqueron Bay on the west. It is the most pronounced physiographic feature of its type in the district. Its south wall is formed by the San German limestone and tuff. The northern boundary is less strongly set off from the low hills of the complex mountain province. Its greatest width is approximately three miles, with a length of over 21 miles. Southwest of Lajas the valley narrows; then widens again westward of that point. The elevation ranges from sea-level at Guanica and Boqueron bays to an altitude of 150 feet just south of Lajas. The underlying rock is chiefly tuff, with small patches of shale and two remnants of San German limestone in the hills east of Guanica Lake. Tuff remnants can be found protruding through the alluvium filling. The geologic structure which has influenced the development of this lowland is that associated with the southward-dipping shales and limestones. Reference to geologic cross-section (B. B^1), Plate V, will illustrate the structural habit of the rocks involved. It will be noted that the formations dip south at angles near 45°, and the main depression is cut on the tuff, with the limestone forming the greater part of the ridge to the south. The history of the development of this valley dates back to a period before the capture of its principal drainage by the Guanajibo. At that time the waters of the Cain, Flores and what is now the upper Guanajibo flowed south to Guanica Bay. It was during this period that the valley was carved. Later diversion of the drainage by the Guanajibo left only a few intermittent streams in the eastern portion, which have continued to furnish water for Lake Guanica. The western portion of the valley was formed by the Boqueron River and its branches.

The depression between Ponce and Juana Diaz differs from the two just described, in that it has been formed on the Tertiary marl and limestone which has an anticlinal structure. Structure (Section H. H^1, Plate VI) is across the eastern part of this valley and shows the relation between structure and topography. The fault along the north side cuts diagonally southwest across the anticline, and in the vicinity of the Ponce-Adjuntas road brings the southern limb, which is composed of chalky limestone, into contact with the Cretaceous rocks. This feature can be seen in Section G. G^1, Plate VI. The south wall is determined by the erosion scarp developed on the south-dipping Tertiary limestone. The surface of this valley does not present the same smoothness which characterizes the depressions at the west end of the district. Low hills are present and stream terraces are cut below the general level of the valley floor.

Other lowlands along the south coast are illustrated by the valleys cut by the Guayanilla, Yauco and Tallaboa rivers. All of these depressions have essentially the same history, having been formed by the streams which now occupy them. Their location and extent are shown on the Geologic Map. Their most conspicuous portions are near the mouths of the streams and are cut in the Tertiary Coastal Plain sediments. In the case of the Rio Yauco and Guayanilla, the valley floors developed on the Tertiary rocks are much wider than along the Tallaboa, but in each case the mouth of the stream is characterized by a coastal flat.

To the east are similar valleys, as, for example, Canas, Inabon, Portugues and Jacaguas, all of which merge seaward into the Ponce Playa.

PLAYAS

Playa is the local name given to gently sloping areas bordering the sea. In other countries similar areas have sometimes been designated as narrow coastal plains, to distinguish them from more extensive tracts of the same character. In Porto Rico, playas are prominent features, especially along the north and part of the south coast. The four most extensive ones in the Ponce District are Ponce, Guayanilla, Mayaguez and Cape Rojo playas.

Ponce Playa, the largest of the four, is over 15 miles long and 3½ miles wide at its broadest point. The gentle seaward slope is traversed by the Canas, Portugues, Bucana, Inabon and Jacaguas rivers, all of which contribute to the gravel, sand and silt which coat the surface of the underlying limestone to depths of 25 feet and over. The topmost layer is generally a black soil, made blacker by fertilization with cane waste from the sugar "centrals."

The formation of Ponce Playa and others to the westward is due to a combination of river flood-plain and delta processes. The detritus from the land has been carried to these lower areas, where it has been spread out by successive floodings. The occurrence of recent marine fossils in the playa material shows the presence, at one time, of the sea over these areas, and its influence in their formation is a factor to be considered.

Guayanilla and Mayaguez playas are smaller than the one at Ponce, but have essentially the same physiographic history. At Mayaguez the underlying rocks are of Cretaceous age, while in the case of Guayanilla the basement formation is of the same geologic age as that at Ponce.

Cape Rojo Playa is of special interest, due to the presence of a thin coating of reddish, siliceous sand which covers the surface. The rock upon which this sand rests is not extensively exposed, but where seen it is tuff of the same general character as that at Ensenada. The origin of the siliceous sand is probably in the numerous quartz veinlets which occur in the shale and tuff; also from chert masses in these rocks. The red color is due to iron oxide coating the grains and preserved in the arid climate which now characterizes the extreme southwest corner of the district. The concentration of sand at this point is most likely the combined work of streams and sea. Conclusive evidence of former streams entering this area from the north was not found, but the gap to the north of the playa suggests the presence at one time of a stream of considerable size. The level character of the surface is in large part the work of the sea when it stood at a higher level.

Minor Physiographic Features

SLUMPING

Slumping has produced minor physiographic changes, especially evident along the sides of river valleys which traverse the Tertiary limestone, and in places the material has been reworked by the estuary waters, which at one time filled the lower portion of these river valleys. The erosion scarp along the north-facing Tertiary has also been modified by the same process. Large quantities of broken Tertiary rock were found in slumped areas, especially along the Ponce-Mayaguez road between Yauco and Ponce. The slumping has covered much of the fault which passes through this section. In the Cretaceous rocks, slumping is best seen in the serpentine northwest of Yauco, near the trail to Maricao. At this locality a large mass of rock has moved a considerable distance down the steep side of the valley. This slide is so recent that the surface along which the movement took place is plainly visible for some distance. Slumping of small areas, especially in road cuts, were encountered on the Mayaguez-Consumo-Maricao road near Maricao. What appeared to be slumping of more ancient date was seen along the steep mountain valleys in the areas of tuff and red shale.

SINK-HOLES

[illegible] examples of sink-holes are far less extensive than elsewhere in [illegible]. The place where [illegible] sink-holes are found is in the [illegible] kilometer [illegible] on the Ponce-Peñuelas road. The field evidence [illegible] that this process has been less important in shaping the [illegible] of the Ponce District than in the case of the Tertiary [illegible] of Porto Rico.

[illegible] south of [illegible] Point

DETAILED DESCRIPTIONS OF FORMATIONS

Tuff

Areal distribution.—Tuff is the most abundant rock in the district. Almost any traverse of the area will disclose a strong development of this class of material. Typical outcrops may be seen at Ensenada and north of Peñuelas. Yauco is underlain by this rock. Other good exposures may be seen along the Yauco-Lares road north of Yauco. On the Ponce-Adjuntas road at intervals between kilometer 15.0 and northward good examples of this rock are to be found. In the broad east-west valley between Yauco and Boqueron occasional remnants of tuff protrude through the alluvial covering of the valley floor.

Thickness.—Due to the pinching and swelling of these beds, whose structure is also very obscure, it is difficult to determine their true thickness. In places where large areas are exposed, it is possible that some duplication exists. The strong folding shown by the shales and limestones would indicate such a possibility. With allowances for such duplication, a conservative estimate of the maximum thickness would be 3600 feet. However, it is possible that sections might be found where this amount would be exceeded.

Lithology.—In general appearance the tuff presents a rather wide variation. Shades of gray, green and chocolate color are common, with yellowish and reddish hues characterizing the weathered material. The texture ranges from very coarse, in which lithic fragments an inch or more in diameter can be plainly seen, to rock so fine that only microscopic study discloses its fragmental habit. The composition is principally andesitic, but trachytic and basaltic varieties have been identified. As these departures from andesitic composition are minor features and are not always apparent in hand specimens, it has been thought best not to attempt separate mapping, but to group all such material under the general head of tuff.

Changes which have been effective since the deposition of the tuff are of two general types:

(1) Induration, which has compacted some beds into a hard, endurable mass which resists weathering even better than some of the igneous types. This induration has involved the formation of carbonitic and epidotitic aggregates, which have acted as a binder for the rock and mineral fragments. The amount of such binding substance is pronounced in some cases and, as can be seen in thin sections, fills the interstitial spaces between the fragments and also replaces rock fragments and crystals.

(2) Weathering, which has disrupted the tuff, thus forming alteration products, chiefly iron oxides and hydroxides, and producing a soft, crumbling mass which can be crushed easily in one's hand. Besides the actual decomposition of the rock constituents, exfoliation has played an important part in the breaking-down process. Large rounded cores of tuff showing exfoliated surfaces are prominent features in the rock toward the southwest end of the area.

Structure is almost entirely absent from rock of this class. Where structure is developed, it is extremely vague and proved of little service in the field. Jointing is pronounced in many exposures, and in places is so well developed that it might easily be confused with bedding. Besides jointing, there are in many exposures a multitude of cross-fractures, some of which have been rehealed with mineral matter, chiefly lime carbonate, giving a veinlike structure to the rock. The gradation of tuff into agglomerate was noted in a few small areas. Rock of this character is made up of somewhat rounded accumulations of rock fragments of the same composition as the tuff proper. bound together by finer material.

In some portions of the mass, attempts at assorting, with the production of partial bedding, could be faintly made out; but massive structure is more characteristic of both the agglomerate and tuff. There are also gradations from tuff into shale, which in some instances is shown by the development of sandy strata. Small, irregular masses of greenish, reddish and grayish chert occur in the tuff, especially in the vicinity of Villalba.

Conditions of Deposition and Age.—The pinching out of beds and the expansion in other areas into deposits of considerable thickness, together with the general lack of stratification which would be expected in waterlain material, are factors which point strongly to deposition upon land of the major part of this rock. The gradation from massive tuff to sandy and ashy beds marks a zone in which the borders of tuff deposits were encroached upon by water bodies and the coarser materials reworked and assorted, with subsequent deposition, into stratified material. The period of tuff deposition ranged throughout the time in which the Cretaceous beds were being formed, deposits of this character being found at the top and bottom and interbedded in the series. There were, however, intervals in which conditions were such as to permit limestone and foraminiferal shales to form.

The geologic age of the Ensenada shale and the San German limestone, as shown by the fossils, is Upper Cretaceous. Since the tuff has an interbedded relation to these formations, and as no unconformity has been found in the series, it is believed that the tuff belongs to the same geologic epoch, namely, the Upper Cretaceous. It is possible that the lowest tuff beds may be Middle Cretaceous or Lower, but there is no evidence to support this view.

Shale

General Statement.—Next to tuff, shale is the most abundant Cretaceous rock in the district. On the basis of composition, a general division may be made into those high in ashy matter and low in lime carbonate, and those high in carbonate of lime and foraminifera remains but low in ashy material. Such a division, although not always applicable in the field, is easily made by microscopic study. A large number of slides from rock of this character, collected in different parts of the district, were studied with this object in mind, and it was found that such a general division like the one mentioned can be made. However, there are gradations between these two main types, and a line of demarkation cannot always be clearly drawn. It was found that the more ashy varieties were confined chiefly to the northern, northeastern and northwestern parts of the district, while the more limy members were nearer the southern boundary. The best structure in the region is that exhibited by rock of this character. Strong bedding and fine lamination are exceedingly well developed. This is true of both the limy and ashy shales, but is generally best seen in the more limy beds. The time that could be devoted to the study of the shales was not sufficient to permit correlation of all the different exposures. Those whose relationships have been partially unraveled and whose occurrence is typical will be discussed somewhat in detail. It is possible that the more limy members are equivalent in part to the ashy representatives, but further field study would be required to prove such equivalency.

Rio Yauco Shale.—Along the road leading north from Yauco are excellent exposures of strongly bedded shale. Rock of this character makes up belts of varying breadth, extending northwest-southeast across the northern portion of the district. The section exposed along the Rio Yauco is typical of this class of rock and exhibits very clearly its structural habit. Similar formations to the east and west have been found to be a continuation of these shales, as, for example, the Jayuya Road shales and the red shale around Mayagüez.

The thickness of shale exposed on the upper Rio Yauco measures 1200 feet. The section here is well exposed and can be measured with some degree of accuracy. At other points it was not possible to get sections suitable for measurement; but, from the quantity of this class of material exposed and allowing for some duplication by folding, it is possible that there is a greater thickness than that stated.

The Rio Yauco shale is characterized by a high content of iron-bearing matter which on weathering has produced large areas of reddish and yellowish soil, and by its thin-bedded and laminated structure, blocky fracture, light weight and porous character. The color, as shown by microscopic examination, is due to the oxidation of iron-bearing minerals, chiefly pyrite. All surface outcrops show some shade of red or yellow, but the unweathered rock is a black shale, as seen in the recently opened quarry at kilometer 6.4+, Mayaguez-Consumo-Maricao road. At this locality the red material, as typically exposed around Mayaguez, can be traced downward into black, unweathered shale. The beds at this point dip with a steep angle, and the change from fresh, black rock through yellowish to reddish material is very striking and furnishes conclusive evidence of the origin of the latter. From a petrographic study of the red and dark-colored shales, Berkey (1915, p. 19) concluded that the former was a derivative of the latter through weathering, but he was unable to trace the change in the field, due to excessive soil covering. In places, as much as 20 feet or more of reddish and yellowish earth covers the outcrops, and it is only in stream beds and in recent excavations that one can find the fresh rock. Trails through areas of this formation are steep and exceedingly slippery, especially during a tropical shower, and a journey over one of them during a storm is an experience long to be remembered.

Bedding and lamination are partially destroyed in the weathered rock, but are prominent features in the fresh, black material. The blocky fracture of the weathered shale was seen in some portions of all the outcrops examined. This feature is lost as the shale passes into soil.

The light weight and porous character are due to leaching, which has accomplished weathering. Cavities are present in varying proportions, as seen in thin sections. In some instances these cavities have outlines suggesting foraminifera shells, but in others the shapes are more suggestive of some mineral fragment. In no case could it be positively determined just what had been removed.

The composition of the Rio Yauco shale is given in detail in the section on Petrology. In brief repetition, it may be stated that the most abundant constituent is a fine, dustlike aggregate of the nature of volcanic dust. In some of the coarser portions of the rock a few angular pieces of feldspar crystals and small lithic fragments are present. Other minerals identified are pyrite (abundant), iron oxide and hydroxide, occurring disseminated through the mass, and carbonate of lime, filling veinlets and irregular spaces, as seen in thin section. Rock of this class grades into and forms small lenslike bodies in tuff. In a number of instances, as, for example, just to the south of San German, a patch of the characteristic reddish Rio Yauco shale can be found in the larger mass of tuff. Such occurrences have been mapped with the tuff in order to reduce unnecessary complexities in areal geological representation.

Irregular bodies of chert, in no instance of great extent, are found in these shales. A good example is on the point which forms the north side of Mayaguez Bay. The chert exposed here is strongly jointed and veined with quartz. It is extremely brittle and breaks with a very ragged fracture.

The bedded and laminated structure of the rock shows that it was deposited in water. The lack of any quantity of minerals which characterize typical sediments and the abundance of ashy matter indicate a volcanic source for the material. The presence of some foraminifera remains shows that conditions were favorable for the existence of these animals. The above facts support the conclusion that shale of this character was formed in a region of volcanic activity where heavy showers of ash were prevalent. Streams draining adjoining land areas of pyroclastic material would contribute to the supply of sediment.

The structural relations of the San German limestone, shales and tuff are those of a conformable interbedded series. Since the age of the San German limestone is Upper Cretaceous, the typical Rio Yauco shale, which carries this limestone as an interbedded member, is undoubtedly of the same geologic age.

Peñuelas Shale.—Thin-bedded, finely laminated, bluish gray rocks, which were found on microscopic examination to contain a large proportion of foraminifera shells, are typically exposed along the military road from Ponce to Peñuelas at kilometer 67.+ (10.+ by old numbers). Due to the fact that the lime content, represented chiefly by foraminiferal remains, is so much more prominent than in the shales just discussed, and also to the uncertainty of correlation of the different shale exposures in the district, it has been decided to treat under a separate group shales which have been found to be equivalent to those exposed at the locality noted above. It is possible that these more limy members are equivalent in part to the ashy shales, as represented by the Rio Yauco beds. The Peñuelas shale was followed westward from the type locality at kilometer 67.+ to the vicinity south of Sabana Grande and San German. From this region it continues on to the west. Beds of similar character north of Ponce and farther to the east may belong to this formation, but the fault marking the boundary between the Tertiary and pre-Tertiary cuts off the beds and makes correlation uncertain.

The thickness of this formation is best measured along the road to Lajas, south of San German. At this point beds aggregating 1000 feet are exposed, and this figure probably represents the maximum for the formation.

The most distinguishing field characters of the rock are its perfect thin bedding and lamination, bluish gray color on fresh fracture, and yellowish surface where weathered; also, high lime content, which at first makes one think that the rock might more appropriately be designated a limestone. However, after studying the whole region and noting the variable composition of these shales and their lithological dissimilarity to the limestone, it is believed that to use the term limestone for such material would be confusing and in many cases inappropriate. In this paper, rocks of the character of the Peñuelas shale will be spoken of as limy shale, to distinguish them from the ashy variety exemplified by the Rio Yauco beds. Typical Peñuelas shale is high in lime content. The carbonate occurs replacing the foraminifera shells and as a component of the groundmass. Other constituents are a fine, dustlike aggregate which is not determinable microscopically, and pyrite, which in some instances shows perfect cubical crystals visible in many hand specimens. No other minerals were identified in the extremely fine material which characterizes this formation.

The strike ranges from northwest-southeast to east and west, with local flexures giving strikes beyond these limits. The dip is north or south, at angles ranging from 25° to 80°. The contact with the tuff is not a sharp one, being obscured by excessive weathering and the intergradational habit of the formations. The relation to the San German limestone is also of a transitional nature. In many localities local bodies of tuff are present, but their extent is limited.

The geological conditions under which shale of the Peñuelas type was deposited varied somewhat from those influencing the formation of the Rio Yauco beds. These variations may have been of local nature only, since there is no evidence that any extended time interval or radical change in geological conditions existed between the formation of the Rio Yauco or any other Cretaceous shale member. The presence of the San German limestone (Upper Cretaceous) as an interbedded deposit in the Rio Yauco beds in the northern area, and in the southern part overlain conformably by the Peñuelas shale, suggests the equivalency of the Peñuelas beds with the upper part, at least, of the Rio Yauco shale. The structural relations of the Peñuelas shales to the San German limestone and other Cretaceous beds to the south are such as to place the former in the Upper Cretaceous.

Ensenada Shale.—The small hill just back of the steamer dock at Ensenada is made up of limy shale containing microscopic fragments of radiolites and foraminifera shells and specimens of ***Hemiaster berkeyi*** n. sp. This rock forms the ridge to the south of the town and can be traced westward to the region just south of Melones Point, on the west coast. The eastward continuation is cut off by the fault between the Tertiary and Cretaceous. Along its westward extension good exposures can be seen just north and also to the west of Parguera. Since the relation of this shale to similar formations in the region is not clear, as will be pointed out later, it is proposed to use a local designation, Ensenada shale, for this rock so well exposed at Ensenada, on Guanica Bay.

The greatest thickness attained by this formation was estimated at 650 feet, but places were found where less than this amount was exposed. The section measured was at the type locality at Ensenada and probably represents the maximum thickness.

The structural habit of this rock is similar to that of the Peñuelas shale, but the fine lamination is not so prominently developed and the color of the fresh material has less of the bluish gray appearance, as seen in the rock at kilometer 67.0, on the Peñuelas-Ponce road. Fragments of foraminifera shells are abundant and sections of *Radiolites* are identifiable. The rock is high in carbonate of lime, which replaces the organic remains, and is also strongly developed in the groundmass. Microscopic examination shows the presence of areas which were at one time volcanic glass and tuff fragments, but are now replaced by lime carbonate.

The strike varies from north 60° west to east and west, with a local flexure at the point where the beds reach Guanica Bay. Toward the west, strikes south 85° west were read, but these were only for short distances. The prevailing strike is nearer east and west. The dip is 42° south at Ensenada, and reaches as much as 85° south north of Parguera. The base of the formation grades into tuff, and the top into sandy, tuffaceous material.

The Ensenada shale was probably deposited under conditions similar to those existing at the time the Peñuelas beds were formed, though the lithologic character of the rock itself would suggest that the water was shallower. It is possible that this shale represents a nearer-shore portion of the Peñuelas beds. Another interpretation, however, would be that the stratigraphic position of the Ensenada shale is higher than that of the Peñuelas. Whatever the stratigraphic relation of the shale at Ensenada may be to other shales in the district, the conditions existing at the time of their formation were not unlike those influencing the formation of such rocks as the Peñuelas shale and similar deposits in the area. There seems little doubt that this shale was formed during the same geologic epoch as the rest of the "Older Series." The structural relations of the rock to those of Upper Cretaceous age and the presence of the *Hemiaster berkeyi* n. sp., whose affinities are with the Cretaceous, lead to the conclusion that this formation is also Upper Cretaceous.

Limestone

San German Limestone.—The areal extent of the San German limestone can best be seen by reference to the Geological Map. It will be noted that the formation has a general east-west trend in places and a northwest-southeast in others; also, that the beds are not continuous, but pinch out. The most typical development of this rock is in the hills southwest of San German, and it is for this locality that the formation has been named. The high erosion scarp which forms the south wall of the San German-Cabo Rojo-Hormigueros Valley partially owes its existence to steeply south-dipping beds of this rock. Exposures of this formation are found at other points in the district, among which are:

(1) Just south of the railroad bridge over the Susua River, on the road to Guanica.

(2) In the limestone quarry at Ensenada.

(3) At kilometers 31.8 and 34.7, on the Yauco-Sabana Grande road.

(4) On the Ponce-Adjuntas road at points shown on the Geological Map.

The greatest thickness determined was 600 feet. In places it pinches to nothing. The best section for measurement is the type locality southwest of San German.

The rock in most cases is a massive, bluish gray, fine-grained limestone, very brittle and showing on weathered surfaces the sieve-like structure of weathered cross-sections of *Radiolites*, so aptly described by Berkey (1915, p. 1) as resembling a piece of loosely woven cloth. In places the rock is filled with fragments of this fossil. Another fossil which was found in the beds southwest of San German, and also north of Yauco and Ponce, is *Actæonella* sp. Both the *Radiolites* and *Actæonella* were identified by Dr. T. W. Stanton, of the United States Geological Survey, who considers them as Upper Cretaceous. In some localities—for instance, at kilometer 14.5, on the Ponce-Adjuntas road—the rock is made up in large part of fragments of *Radiolites* and *Actæonella*, which have given the material a shred-like character. This rock has been called "shred" limestone by Berkey. On many weathered surfaces the mesh form of weathered *Radiolites* can be seen, and was the index by which the beds were traced across the district. The *Actæonella* sp., although occurring in many outcrops, was not found at all points.

Typical exposures of this limestone are generally massive, exhibiting but little of the bedded character. In the massive material, jointing is prominent and weathering has progressed along joints and on the surface, producing a white lime soil resembling very much the powdered Tertiary limestone. This feature is very well shown in the quarry at Ensenada and along the road from the quarry to the "Central"; also on the south side of Yauco-Boqueron Valley. Weathering has also produced pitted surfaces on the exposed rock, the rounded depressions sometimes measuring over two inches in diameter. When examined microscopically, the limestone was found to contain numerous fragments of *Radiolites* and portions of foraminifera shells. Carbonate of lime makes up the remainder of the rock. At some localities, as, for example, along the Yauco-Lares road at kilometer 9.0, the limestone is involved in a crushed zone and has been intensely crushed and broken, inclosing fragments of igneous rock which are chiefly andesite. Other exposures where crushing has taken place are along the Ponce-Adjuntas road at kilometer 16.8 to 16.9 and 18.7; also three miles northwest of Maricao.

During the period of formation of the San German limestone conditions were favorable for the abundant development of *Radiolites,* which grew in reef-like colonies. The character of the rock indicates a decrease of volcanic activity in the region. The lens-like nature of the beds suggests local areas of deposition, and the structural relations of the beds to other formations points to a single period of deposition for all the beds of this limestone. The Upper Cretaceous age of the rock is determined by the presence of *Radiolites* sp. and *Actæonella* sp.

Coama Tuff Limestone.—The best development of the Coama tuff limestone in the Ponce District is in the section exposed along the east branch of the east fork of Jacaguas River, north of kilometer 113.0, Ponce-Juana Diaz-San Juan military road. The structural relation of this rock to the formation associated with it can be seen in cross-section (H. H[1]), Plate VI. A very good exposure of this limestone is along the Descalabrada River, at the crossing of the military road.

The section along the east fork of Jacaguas River measures 250 feet and probably represents the greatest thickness of this formation.

The Coama tuff limestone presents the most striking lithologic characters of any rock in the district. In typical specimens it is made up of angular fragments of white, grading to cream-colored limestone, mixed with igneous rock fragments, some of which measure two inches, but the greater number of much smaller size. The composition of these igneous fragments is chiefly andesitic, and their color when weathered is, as a rule, a chocolate hue, which, in contrast with the whitish limestone fragments, gives the mass a very unique appearance. In some specimens the limestone fragments are of a bluish gray color, resembling closely the typical San German formation. The beds exhibit little structure, being prevailingly massive in character. They grade into tuff below and shale above. In the section exposed in the Ponce District the beds stand nearly vertical and strike northwest-southeast; but on the Descalabrada River, just west of the area considered in this report, the formation has a gentle southward dip and is folded into a distinct monocline.

The formation of this unusual lithologic type necessitates the breaking up of previously formed limestone and igneous rocks and subsequent deposition of the resulting fragmental material. Such conditions can be accounted for by volcanic activity in the form of outbursts through previously formed rock, and the deposition of this broken material to give a new formation.

The presence of *Radiolites,* together with the stratigraphic position of the strata, places this formation in the Upper Cretaceous. The true relation of this rock to the San German limestone could not be determined

It is probable that it is in part equivalent to the San German, but was deposited under different conditions.

Guayabal Limestone.—The type locality for this formation is the vicinity of Guayabal Reservoir north of Juana Diaz, where the rock makes up the conspicuous white hills to the east and west of this point. Berkey tentatively placed this formation with the Coama tuff limestone, but the section exposed on the upper east fork of Jacaguas River shows the typical Coama tuff beds overlain by limy shale, upon which follows the Guayabal limestone. As stated in the discussion of the Coama tuff limestone, its stratigraphic position below shale identical with the Peñuelas shale and the presence of *Radiolites* in the limestone indicate a close relationship between the Coama tuff limestone and the San German formation, but necessitates different conditions of deposition. Since field relations show the Coama tuff limestone and the limestone at the Guayabal Reservoir not to be equivalent, it is proposed here to use the term Guayabal limestone for the white, massive rock developed in the vicinity of Guayabal Reservoir. This formation continues southeastward in prominent development into the adjoining district studied by Hodge (1920). To the west, beds of this character were traced northwestward for three to six miles, when they were found to pinch out. Whether or not they are developed in the district to the north cannot be said. It is possible that their development is local and they will not be found in the area north of the Ponce District.

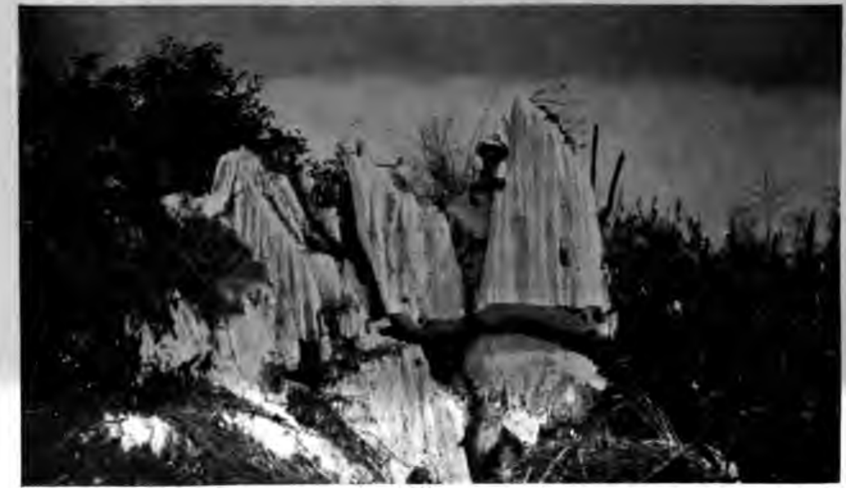


FIG. 3.—*Fluted Guayabal limestone north of Juana Diaz*

The section on the upper east branch of Jacaguas River proved the best for determining the thickness, which measured 950 feet.

Hand specimens of this limestone are a mottled cream color, with dendritic manganese marking some of the rock. The material is massive and brittle, breaking easily under the hammer. In some exposures jointing is prominently developed, but this is not true of all the material. Bedding is rather obscure, but the true attitude of the formation can easily be determined from the structure of the underlying shale. A considerable quantity of fragmental organic remains are present, including *Radiolites* and foraminifera. The beds strike north 50° to 65° west and dip south 25° to 35° on the north limb of the syncline, and stand nearly vertical on the south side of the fold. It is in this rock that the manganese north of Juana Diaz is found.

Differential weathering has produced a characteristic fluting in portions of the outcrop. The narrow channels stand vertical and are sometimes two inches wide and over three feet in length. In figure 3 a good illustration of this fluting in the white limestone is shown. Diller (1897) describes fluted limestone from Baird, Shasta County, California, of which he says:

> This limestone is exposed in large masses, making a mountain ridge along the McCloud River. At many points its surface bears peculiar small ridges and intervening depressions. In the field it is evident that the little valleys are lines of drainage, and it may readily be concluded that they are a form of rain erosion due to the solvent action of the water running over the surface. An examination of many ridges and valleys discloses no difference in composition or structure to which the variation in surface form may be due. From the fact that the flutings are drainage lines, it appears that they may be referred to the rilling of the water on the surface of the limestone. Where the water flows the solvent action is most intense, and a minute valley is formed by solution. This form of differential weathering is common upon limestone exposures, but is rarely so well developed as in the example from which specimen 154 was collected.

The fluted character of the Guayabal limestone is a very striking feature where strongly developed and probably has the same origin as that described by Diller.

The noticeable absence of fragmental volcanic material would indicate a period of decreased vulcanicity. The presence of *Radiolites* places the limestone in the Upper Cretaceous. Its structural relation to the Coama tuff limestone, which is probably equivalent to part of the San German formation, would place the Guayabal limestone in a higher position in the Upper Cretaceous.

TERTIARY SEDIMENTS

INTRODUCTORY STATEMENT

The Tertiary sediments along the south coast of Porto Rico extend from a short distance beyond the southeastern section of the Ponce District westward to Point Aguila, in the southwest corner of the island. They represent a former more extensive coastal plain series deposited upon and partially around an eroded central core of complex rocks. Whether or not these later sediments formerly extended across to the north coast cannot be determined, but the evidence is clear that they once had a greater extent northward. Their stratigraphic relation to the Cretaceous formations has been complicated by the fault which determines the northern limit of these rocks. However, other structural features are such as to show without doubt that the conditions were similar to those on the north coast, where the Tertiary rests with a marked unconformity upon the older formation.

In general, the Tertiary formation is made up at the base of fossiliferous, yellowish, marly material with occasional sandy layers. This basal portion grades into the yellowish and white, chalky limestone characterizing the upper portion. The highest strata contain fragmental masses of coral heads bedded in soft, chalky material. Some harder strata of pinkish semi-crystalline limestone, at times a foot or more in thickness, are found in the higher, chalky portions. From its typical development in the region around Ponce, it is proposed to use the name of that city to designate this formation.

PONCE FORMATION

The Ponce formation is confined to remnants of variable extent along the southern border of the district. The largest area is northwest and west of Ponce, where the chalky limestone is best developed. To the east of Ponce, and underlying the Ponce-Juana Diaz Valley, is found the best exposure of the lower marly and shaly portion. The upper part of these lower beds is found at the fault contact just east of Yauco and at other points along the military road from Yauco to Ponce; also in the face of the hills just south of Yauco.

The lowest beds are made up of yellowish, marly and shaly material in which sandy and more compact strata are developed. These harder layers are sometimes two feet or more thick and contain abundant foraminifera (*Orbitoides mantelli*), which fossil also characterizes the more shaly and softer portion of the rock. Other fossils identified in the collection from the lower beds include *Laganum* sp., *Pecten* sp., *Fasciolaria* sp., *Cythara* sp., *Turritella halensis, Turritella halensis* var. *alpha, Cardium* sp., *Astarte* sp., *Cypræa* sp., *Amphistegina lessoni* (abundant), *Ensis* sp., leaf fragments and fish teeth. Pieces of petrified wood are also present and coal is reported to occur in these beds, but none was found. Besides the sandy portions, there are thin layers of fine gravel in which shell fragments are plentiful. Some of the sandy layers are filled with broken shells and foraminifera, especially the forms *Amphistegina lessoni* and *Orbitoides mantelli.* The lower beds pass disconformably into the upper yellowish, chalky limestone so well exposed in the hills around Ponce. This material is characterized by its yellowish white color and chalky nature. It contains numerous casts of *Lucina* sp., *Arca* sp., *Bulla* sp., and other forms. In structure it is generally massive, but hard, thin, yellowish strata are prominent in some localities and are valuable in determining the structural habit. The chalky material continues to the top of the formation, which, if anything, becomes more chalky. The uppermost beds are well exposed along the coast from Culebrinas Point to Guanica Bay. At Culebrinas Point the rock contains abundant specimens of *Clypeaster rosaceus,* together with other forms of Oligocene age.

The basal portion of the Ponce formation was deposited in comparatively shallow water near shore, as shown by the sandy character of the strata, together with the abundance of broken fossil fragments and remains of plants. The distribution suggests a broad embayment whose eastern limit was located approximately a short distance east of Juana Diaz and whose western extent was in the vicinity of Yauco, though faulting has made it impossible to determine the exact extent of these lower beds. How far north this embayment reached is not certain, but, judging from the lithologic character of the rock and structural features, it was certainly more extensive than at present.

The present width of the island on a north-south line through Juana Diaz is approximately 34 miles. The distance between the Tertiary of the north and south coast along this line is about 18 miles and the elevation of the highest point nearly 3600 feet. Considering the fact that the central mountain mass was much lower at the beginning of the Tertiary period, as shown by the peneplane developed on the north side, it would appear that the lower beds of the Tertiary must have been laid down much to the north and south of their present boundaries, on the two sides of Porto Rico at about its central portion. The conditions influencing the deposition of these lower beds changed to those under which the chalky material was formed. In this later period more quiet and deeper water prevailed, with a continuance of these conditions through the Oligocene at least, as no record of further deposition is found until the San Juan formation (Pleistocene) is reached. The question as to how extensive the upper beds were is also unsolved. They surely reached farther north, but whether or not they covered the island cannot be determined from any evidence thus far secured. The fact that there is a difference in the Tertiary fauna of the north and south coast, as far as can be told from the fossils already identified, is a fact to be considered in this connection. Further detailed studies of the fauna from the north and south coasts may prove or disprove a former connection.

The lowest beds, as exposed along the Jacaguas River northwest of Juana Diaz, are characterized by abundant *Orbitoides mantelli.* They are forms which establish the Oligocene age of the Ponce formation, with the basal portion of Lower Oligocene (Vicksburg age) and the higher part representing Upper Oligocene (Chipola).

QUATERNARY DEPOSITS

SAN JUAN FORMATION

The San Juan formation, first identified and named by Berkey (1915, p. 11), is found at Cape Rojo Lighthouse, in the southwest corner of the district. At this locality it caps the eminence upon which the lighthouse stands.

The rock at Cape Rojo has the same general characters as that of material in San Juan Point. Æolian cross-bedding is present and the rounded grains of carbonate of lime which make up the bulk of the formation are plainly visible in hand specimens. A conglomerate bed three feet thick, made up chiefly of pebbles of Cretaceous rocks, is found resting on the San Juan at the edge of the cliff south of the lighthouse. This is a feature not seen at San Juan. The relation of the San Juan to the Ponce formation is unconformable. Details of the petrographic character of this rock, which is one of the most interesting types found in the district, will be discussed under Petrology.

The unconformable relation of the San Juan to the underlying Tertiary limestone, as shown in the cliff at Cape Rojo, necessitates a period of erosion at the close of the Tertiary sufficient to bevel the underlying beds. Just how much erosion has taken place is not known, since the latest Tertiary record in the district is Upper Oligocene, and there is no evidence that Miocene or Pliocene strata were ever deposited.

The presence of æolian cross-bedding indicates a dune origin. The capping of conglomerate made up of well-rounded pebbles and the presence of *Conus* sp., which resembles *Conus portoricanus,* show that the San Juan was at one time below sea-level. The age of this formation has been placed as Pleistocene (Berkey, 1915, p. 12). The fossil content and situation of the beds at Cape Rojo support this conclusion.

ALLUVIUM

Alluvial material can be found along all streams and mantles the greater part of the broad lowlands near the coast. The low coastal regions known as playas are coated with deposits of this nature to a depth of 25 feet or more.

Deposits of this type are composed of material ranging from boulders two feet and over in diameter to the finest silt. An examination of the gravel shows representatives of the range of rocks in the Cretaceous formations, and in some deposits nodules of Tertiary limestone are present.

That some of this material was deposited when the land stood at a lower level is shown by the presence of interstratified, recent marine fossils in the surface layers of the playas and river floodplains and in elevated estuarine sediments. It may be noted that the alluvial material can be grouped under two general heads:

(1) Elevated estuarine gravels, mud and silt, occurring along the present river valleys.

(2) Deposits of the same character, covering the present river floodplains and playas and being augmented by each successive flooding. The first might better be correlated with the San Juan formation, while the latter would represent the more recent deposits.

Igneous Rocks

For purposes of mapping, the igneous rocks have been divided into diorite, andesite, diabase, and augite porphyrite. The occurrences of quartz diorite are too small to be shown areally on the geologic map. This is also true of the trachy-andesite. However, due to the petrographic interest of these rocks, they have been discussed in detail under Petrology, where will also be found a more extended discussion of the igneous rocks.

All of the igneous rocks in the area have an intrusive relation to the Cretaceous sediments and occur as dikes, sills and irregular masses. The largest intrusive is represented by peridotite altered to serpentine in the region north of Sabana Grande. The dikes and sills range from thin sheet-like bodies to masses 50 feet or more in thickness and are all confined to the Cretaceous formations. In no instance were intrusives found cutting the Tertiary rocks. The general elongation of the intrusive bodies along the strike of the pre-Tertiary beds is a noticeable feature.

METAMORPHIC ROCKS

ANAMORPHICS

The anamorphics, including garnetiferous limestone, epidote rock, and garnet rock, are typical contact metamorphic effects produced by igneous intrusions in limestone. The extent of these rocks is limited to small zones. They are of particular interest in connection with the associated iron deposit on the upper Portugues River. Further details of these rocks will be found in the section on Petrology.

KATAMORPHIC ROCK

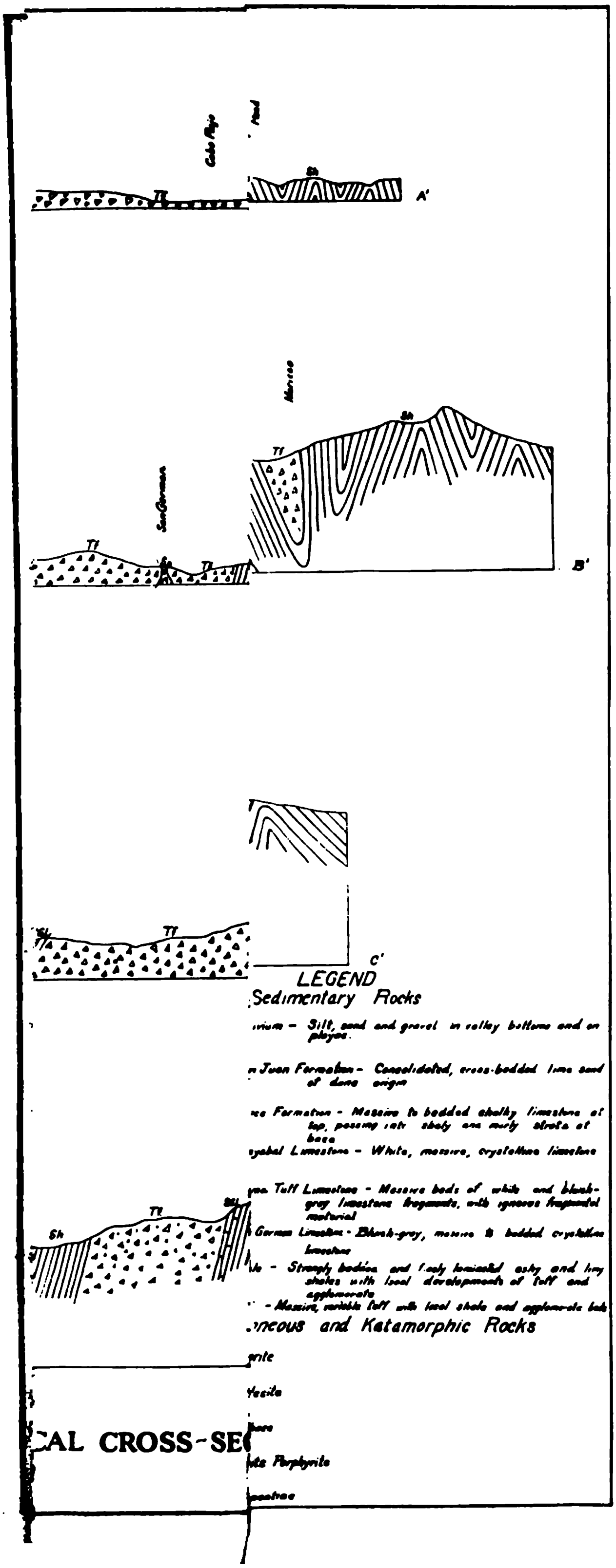
The original peridotite from which the serpentine has been derived was intruded into the tuff and shale of the pre-Tertiary series. This intrusive relation is clearly shown in the area north of Sabana Grande, where small beds of tuff are found inclosed in the serpentine. At other points, as, for example, southeast of Mayaguez, the serpentine cuts across and lies along the bedding in the ashy shale, thus placing the age of this rock as later than the deposition of the Upper Cretaceous and before the formation of the Tertiary, namely, in late Cretaceous time. In all probability the intrusion of the original peridotite was an accompaniment of the folding which deformed the pre-Tertiary beds.

STRUCTURE

INTRODUCTORY STATEMENT

On the basis of structure, the Ponce District is readily divided into two sections—a northern, more extensive area, made up of strongly folded Cretaceous rocks, and a southern border of Tertiary and later formations. The structural habits of these two sections are so strikingly different that one cannot help being impressed by the fact. The marked degree of folding which has affected the Cretaceous rocks, in places throwing them into closely folded, steeply dipping beds, is not to be found in the Tertiary formations.

In an attempt to unravel the structure of the different beds, seven main traverses were made across the area from north to south, along lines which gave promise of the best results. One shorter, north-south, section was studied in detail, and the formations between the main traverses were



Cabo Rojo
Pond
Tt
Sh
A'
Maricao
Sh
Tt
San Germán
Tt
Tt
B'
Sh
Tt
C'
LEGEND
Sedimentary Rocks
…vium - Silt, sand and gravel in valley bottoms and on playas.
…n Juan Formation - Consolidated, cross-bedded lime sand of dune origin
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…yabal Limestone - White, massive, crystalline limestone
…on Tuff Limestone - Massive beds of white and bluish-gray limestone fragments, with igneous fragmental material
…Germán Limestone - Bluish-gray, massive to bedded crystalline limestone
…le - Strongly bedded and finely laminated ashy and limy shales with local developments of tuff and agglomerate
… - Massive, variable tuff with local shale and agglomerate beds
…neous and Katamorphic Rocks
…nite
…esite
…base
…ite Porphyrite
…pentine
Sh
Tt
Sh
…CAL CROSS-SE…

traced east and west. In this way it was possible to locate all field units of any consequence, and work out in some detail the structural relations of the different beds. The making of such traverses in this region is no easy task. The rank growth of tropical vegetation and the ruggedness of the country, combined with excessive weathering of rock exposures, make geological work exceedingly arduous. One factor, however, which facilitated the work was the presence of numerous trails and roads along which it was possible to secure data which probably could not have been acquired otherwise. Many streams afforded sections which helped in determining structural relations. The data collected along the traverses, which in all cases were necessarily sinuous, have been projected to straight lines, as represented in the cross-sections.

FOLDING

LATE CRETACEOUS FOLDING

The strong folding of the Cretaceous formations is the most striking structural feature of the area occupied by these rocks. The dynamic forces involved have produced rather closely folded, steeply dipping, and in cases overturned strata, which in some instances are accompanied by thrust faulting. Dips of 90° were recorded, but the prevailing angles of inclination are usually between 45° and 75°. In the southern part of

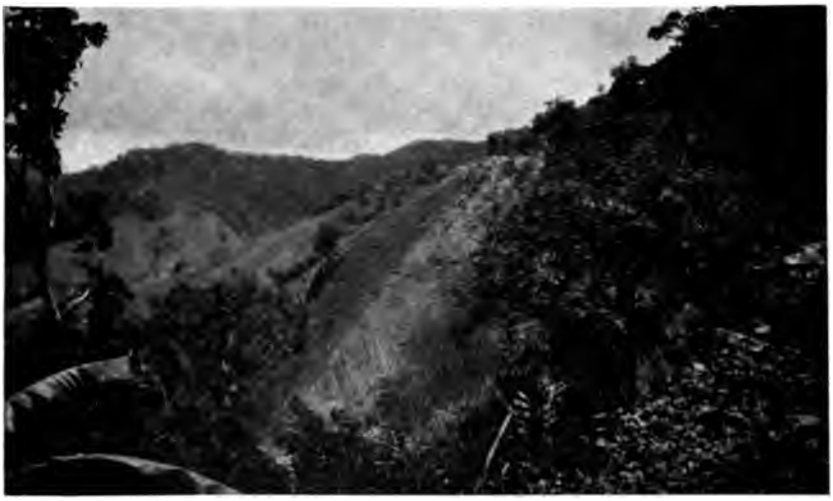


FIG. 4.—*Rio Yauco shale, as seen from point one mile north of kilometer 15.0, Yauco-Lares road*

this northern area the beds are generally overturned to the northeast, but on reaching the summit of the main range, along the northern border of the district, the steeper slopes are more often on the southwest side. This would indicate thrusting from the southwest and northeast. The broader features of these foldings are shown on the cross-sections, Plates V and VI. The general strike of the beds is northwest-southeast in the northern half of the area, with a change to east-west along the southern border, as seen in the region around and west of Ensenada. Variations between these directions are due to local flexures or mark the ends of pitching folds, as is well shown by the shales along the Yauco-Lares road north of Yauco. The section exposed along this road affords the best illustration of folding in the Cretaceous rocks. Here is found an almost continuous section, involving shale, tuff, limestone and igneous intrusives whose structural habit is shown in figure 4. Other localities where the structure of the Cretaceous rocks is clearly shown are:

(1) On the road from San German to Lajas.

(2) Along the Ponce-Adjuntas road.

(3) Peñuelas-Ponce road, especially in the vicinity of kilometer 67.0.

(4) In the region around and west of Ensenada.

(5) South and west of Cabo Rojo.

(6) North of Peñuelas.

(7) North of kilometer 114.0, on the Ponce-Juana Diaz-San Juan military road.

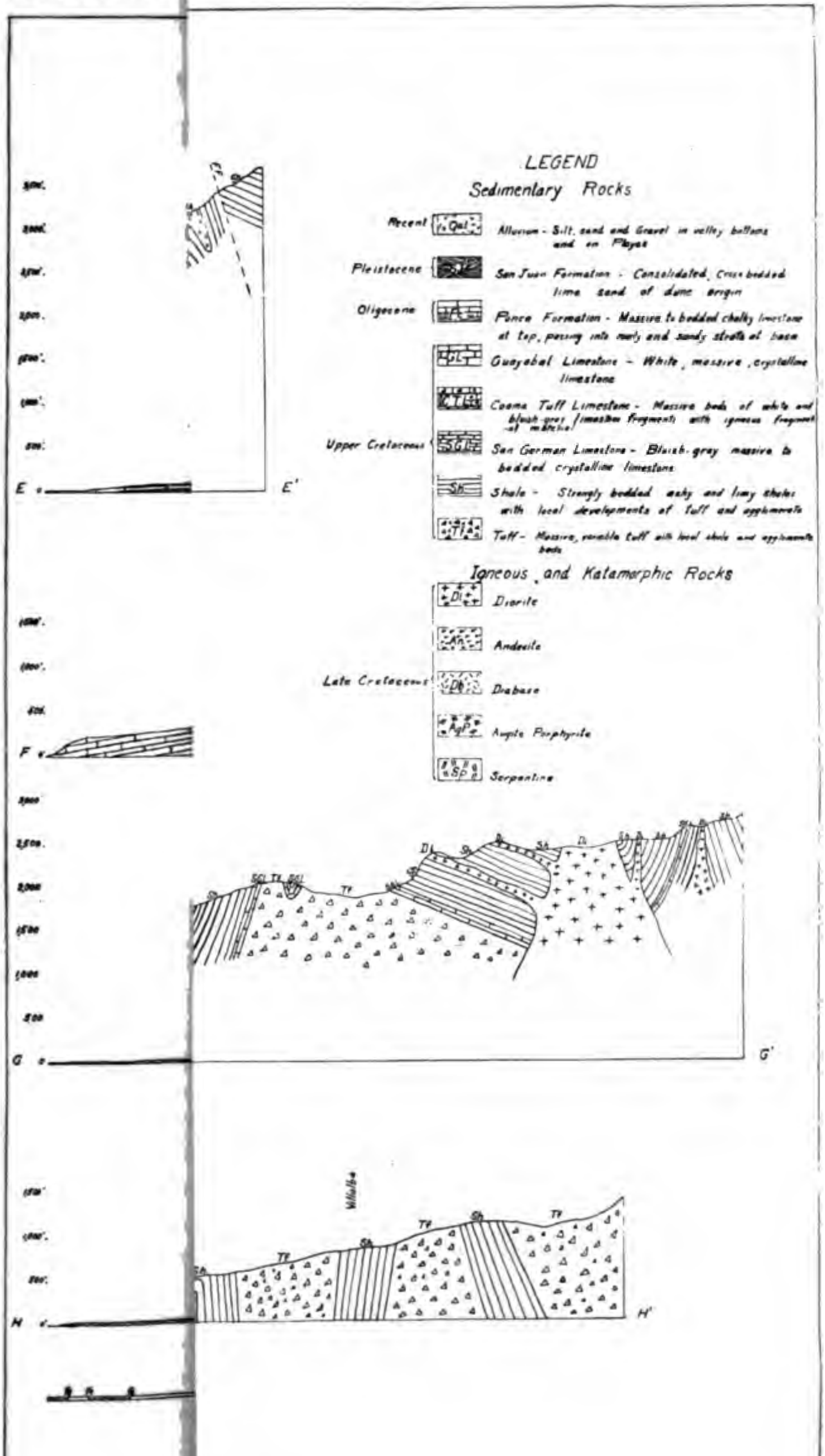
(8) On the upper Bucana River, northeast of Ponce.

In addition to the larger foldings, there are innumerable smaller crumplings, which are not shown in the cross-sections. Examples of local distortion can best be seen in the shale along the Jayuya road, at kilometer 3.0 and vicinity; also at kilometer 22.7, on the Ponce-Adjuntas road.

The presence of such marked folding necessitates the action of mountain-building forces comparable in part to those which have affected regions like the Appalachian Mountains. While the forces which deformed the Cretaceous of Porto Rico have not been active over so long a period as is attributed to those which folded the Appalachians, still the two regions, from a structural standpoint, have features in common. It does not seem possible to attribute the folding of the Cretaceous formations of Porto Rico to igneous intrusions, although such an hypothesis has been advanced.

FOLDING OF TERTIARY

The Tertiary limestone and marl comprising the Ponce formation have been folded to the extent of producing low anticlinal deformation, which


LEGEND
Sedimentary Rocks
Recent
Qal
Alluvium - Silt, sand and Gravel in valley bottoms and on Playas
Pleistocene
SJ
San Juan Formation - Consolidated, Cross bedded lime sand of dune origin
Oligocene
P
Ponce Formation - Massive to bedded chalky limestone at top, passing into marly and sandy strata at base
GL
Guayabal Limestone - White, massive, crystalline limestone
CTL
Coamo Tuff Limestone - Massive beds of white and bluish-grey limestone fragments with igneous fragments of matchel
Upper Cretaceous
SGL
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Igneous and Katamorphic Rocks
Di
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An
Andesite
Late Cretaceous
Db
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AgP
Augite Porphyrite
Sp
Serpentine
E
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G'
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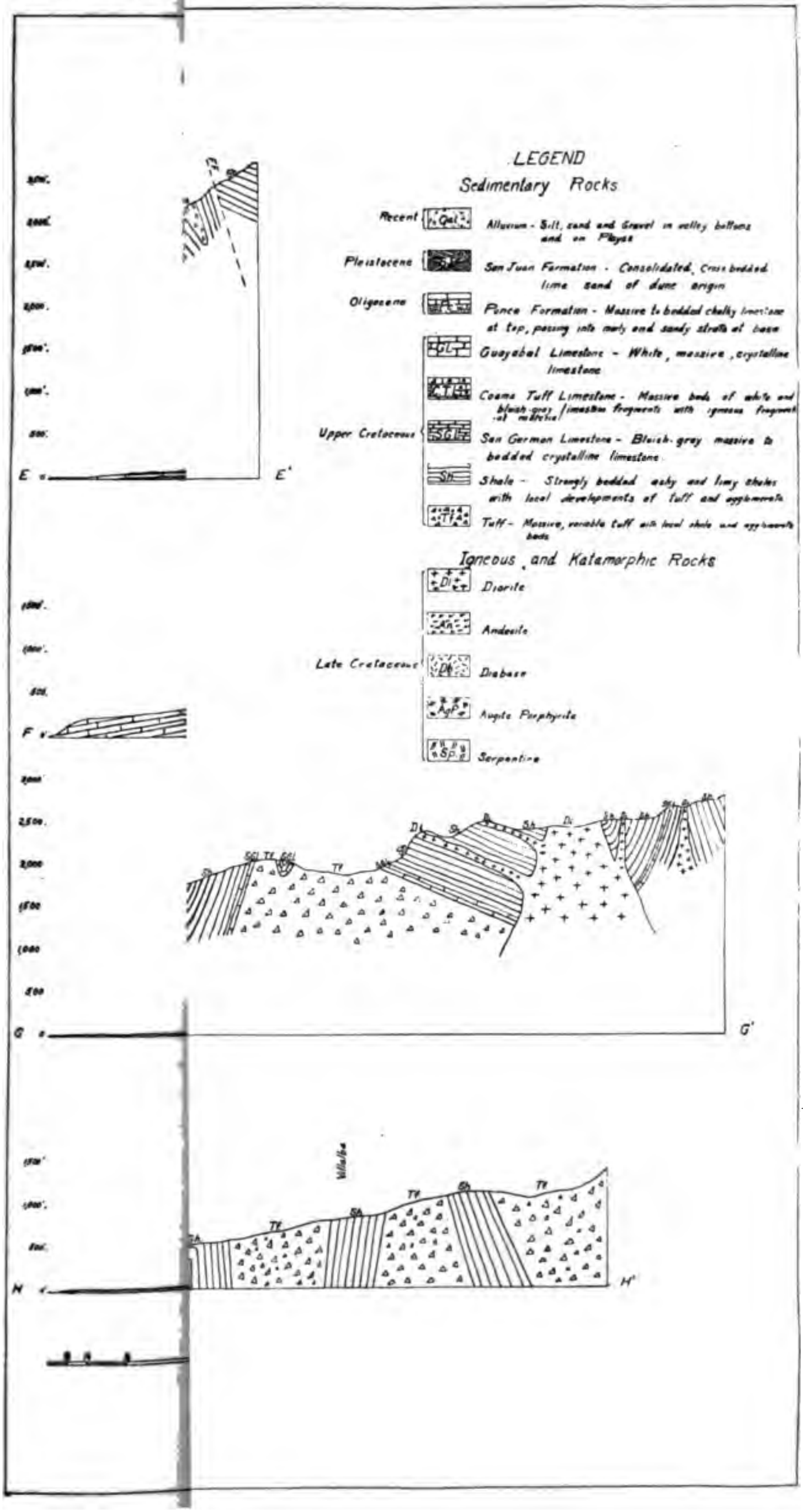
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Tf

in places pitches with low angles to east and west. How extensive this folding has been cannot be determined, because the fault which marks the boundary between the Tertiary and Cretaceous rocks cuts out the lower part of the Tertiary beds, and thus conceals their structural habit. That folding has taken place is clearly shown in the section (H. H^1, Plate VI) along the Jacaguas River, north and south of the Ponce-Juana Diaz road crossing. At this point anticlinal structure of the formation is present, with the crest of the fold just north of the Jacaguas River bridge. The north limb of the fold dips with an angle of 15° to 10° into the fault bounded on the north by the tuff. On the south side of this anticline the beds are exposed in the prominent erosion cliff plainly visible to the southwest from the Jacaguas River crossing. Here the strata dip from 35° to 10° southward; the steeper dips are in the face of the cliff, and become more gentle north and south of this point. This is the only locality where such pronounced dips in the Tertiary rocks occur. In general, the inclination is from 10° to 20° southward, the steeper angles being read on strata near the fault zone, and are due in part to dragging up of the beds by faulting. Besides this folding, with axes trending approximately east and west, there are broad, shallow deformations which have nearly north-south axes. This latter folding was determined by tracing the marl and limestone beds from east to west.

The Tertiary formation shows none of the minor crumpling so characteristic of the pre-Tertiary. The absence of structural contortions comparable to those in the Cretaceous beds clearly indicates a period of diastrophic movement much inferior to that which affected the older rocks.

FAULTING

IN CRETACEOUS ROCKS

By far the greater number of faults in the Cretaceous rocks are of the normal class, although, in some instances, as along the Jayuya road, at kilometer 3.0, the shales have been overturned, accompanied by thrust faulting. Other evidence of faulting in the form of crushed zones was seen in many localities (Fig. 5); for example, at kilometer 9.0, Yauco-Lares road, where limestone, tuff and igneous rocks are involved in the crushing, and on the Ponce-Adjuntas road, at kilometer 17.0 and 16.8+, where the limestone is extremely crushed and broken, due to faulting. Other localities are in the region north of Peñuelas; along the main drainage divide west of Adjuntas; northwest of Villalba; southwest of San German; north of Hormigueros, and at many other places too numerous to list here. In the majority of cases examined no great displacement had taken place, which would indicate that the intensity of such deformational forces was not so great as has been the case in other regions of mountain-making.

The most conspicuous faults in the Cretaceous formation are shown in the structure section (B. B^1 and C. C^1, Plate V). In the first instance the rupture has occurred in the serpentine and is marked by the intensely crushed and slickensided condition of the rock, as well as by physiographic features. In the section C. C^1, the break has taken place along the contact of serpentine and shale. The amount of movement in either case could not be determined. In both cases the physiographic expression supports structural evidence of faulting.

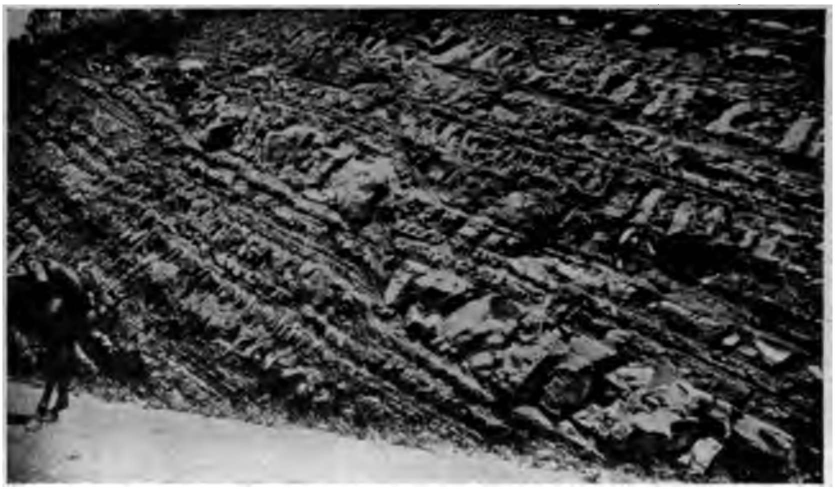

FIG. 5.—*Faulted shale at kilometer 14.3, Yauco-Lares road*

LATE TERTIARY FAULTING

The most pronounced fault in the district is the one marking the contact of the Tertiary limestone and marl on the south, with the Cretaceous formations on the north. Berkey (1915, p. 39) was the first to call attention to this structural feature, and he says:

> The most prominent fault, in its effect upon present features, is the one now marking the inner margin of the younger series of chalky limestones and shales constituting the coastal belt along the south side of the island from Juana Diaz past Ponce a short distance to the north, crossing the Ponce-Aricebo road at K-4.8, and thence westward, crossing the Ponce-Peñuelas road at K-10. This is the only large fault actually observed that is necessarily of

recent age, although a few others are inferred. It must be of very late Tertiary age, because the chalky Ponce beds are abruptly cut off by it. The older rocks of the pre-Tertiary are lifted with respect to the younger series, forming the present coastal margin wherever this fault has been seen. It has been traced by us from Juana Diaz to the vicinity of Peñuelas, a distance of about 12 miles. What becomes of it at either end is not yet determined, but it is believed to extend much farther in both directions.

Further evidence secured by the writer during field studies in this district substantiates the conclusion reached by Berkey and has also made possible the tracing of this structural feature to a greater distance east and west. The additional evidence relating to this question has been secured at a number of localities, extending from the vicinity of Juana Diaz to a point five miles east of Point Melones, on the west coast. The most eastern locality where faulting is clearly shown is on the Jacaguas River, northwest of Juana Diaz. The structural relations of the Tertiary marly limestone to the Cretaceous tuff are shown in cross-section H. H¹, Plate VI. It will be noted that the folded Tertiary beds have been dropped down against the upraised tuff. If these Tertiary beds were raised sufficiently to allow them to lap over the eroded surface of the Cretaceous formations, which they must have done before their displacement, then we would find that the movement down the steeply inclined dip slope of the fault plane was at least 900 feet. However, the base of the Tertiary is not exposed; so the exact amount of movement which has taken place cannot be measured. The contact between the marly beds and the tuff is represented by a crushed zone over 50 feet wide, in which tuff and marly material are mixed with surface wash. The evidence of faulting to the east of this point is concealed by the alluvial cover; but, judging from the position of the Tertiary and Cretaceous beds and the presence of crushed zones, the fault is believed to cross the Ponce-Juana Diaz-San Juan military road in the vicinity of kilometer 112.0 and continue southeastward beyond the limits of the district. Going westward from the Jacaguas River, the fault can be traced to the Ponce-Adjuntas road where it crossed at kilometer 4.8. Here the Tertiary chalky limestone is separated from the tuff by a crushed zone over 100 feet wide. The Tertiary beds are dragged up so that they dip 20° south near the fault and flatten out to 12° and 10° a short distance southward. Continuing westward to the west fork of Canas River, the same relations as seen on the Ponce-Adjuntas road are found.

The next locality to be considered is kilometer 67.0 (10.0 by old numbers), on the Ponce-Peñuelas road. The structural relations of the Cretaceous shales and Tertiary limestone are shown in cross-section F. F¹. The folded shales have been raised so as to cut out the lower Tertiary beds and bring the chalky limestone in contact with the Cretaceous rocks. This contact is also marked by crushing, and the Tertiary beds are sharply turned up against the older rocks. From this point the fault passes south of the military road, and the next locality where the evidence is clear is just south of kilometer 48.0, on the Yauco-Peñuelas road, east of Yauco. At this locality the marly beds just below the chalky limestone are turned up against the Cretaceous rocks, with a narrow zone of crushed material lying between.

Passing farther west, the line of faulting runs north of the base of the Tertiary limestone and marly material forming the hills just south of Yauco. Here structural relations are concealed by the alluvium of the valley; but farther west, in the region of the San German limestone outcrop, at the east end of the railroad bridge over the Susua River, the faulted relations are again conclusive. At this point, which is three-fourths of a mile southeast of the railroad bridge, the white, chalky Tertiary formation is sharply dragged up against the San German beds. The crushed zone, which is approximately 20 feet wide, is filled with powdered Tertiary limestone and fragments of the San German. South of the contact, chalky Tertiary limestone assumes a normal dip of 10°, which is the average inclination maintained to the south coast. Three miles farther southwest the same relations can be seen. Here the San German limestone and the Tertiary chalky beds are again involved in the displacement. From this point the line passes southwest to Ensenada, where the Tertiary and Cretaceous are brought in contact. The relations here are best seen on the south side of the ridge of Cretaceous shales south of Ensenada. By following westward along the south face of the ridge, the chalky limestone is found to approach the older shales where the former is upturned against the steeply dipping Cretaceous. The dip of the Tertiary south of the contact is 8° to 12° south. The narrow crushed zone between the formations is filled with powdered, chalky limestone, fragments of shale, and surface wash.

In structural section B. B^1 the same relations as seen west of Ensenada are found to be present. The sharply upturned Tertiary limestone abuts against the Cretaceous shale, with a narrow zone of crushing between. Westward, beyond this point, the break has been traced to the playa of Cape Rojo, where it passes beneath the red sand deposit which covers that low coastal area.

In conclusion, the evidence as shown by the structure sections clearly indicates faulting between the Tertiary and Cretaceous rocks. The Jacaguas River section affords the only opportunity for measurements of the displacement; but, as already noted, the exact amount of movement

System
Quaternary
Tertiary
Mesozoic

cannot be determined and is probably much greater than the figure given. The age of this disturbance was at least late Tertiary, since the upper Oligocene beds are involved in the movement. The total displacement is the sum of a number of slippings at intervals throughout the later Tertiary. That the region may still be subject to further structural deformation is indicated by the rather strong earthquakes which were felt during the month of August. Besides the structural evidence already presented, the physiographic habit of the island, as pointed out by Berkey, supports the view of faulting with uplift of the island as a whole, along the southern side, and tilting of the block to the northeast. The presence of the fault along the southerly margin of the island has been questioned by Dr. A. K. Lobeck. After a study of the physiography of Porto Rico, he has concluded that the evidence of faulting can be attributed to sink-hole formation along or near the contact of the Tertiary and Cretaceous rocks. The abnormal dips of the beds near the fault he attributes to drag, produced by caving action accompanying the sink-hole formation. Such a "sink-hole hypothesis" seems incapable of explaining the structural features involved.

PETROLOGY

INTRODUCTORY STATEMENT

The purpose of this chapter is to summarize the petrographic details of a selected set of typical rocks from the area investigated. The material chosen includes sedimentary and igneous representatives, most of which are of sufficient field extent to be shown on the geologic map of the district. Some contact metamorphics are also described, but are not differentiated from formations of which they are only an altered portion.

IGNEOUS INTRUSIVE ROCKS

QUARTZ DIORITE

Rocks of this type are well exposed at kilometer 23.4, on the Ponce-Adjuntas-Aricebo road, and where seen occur as an intrusive in the form of dikes or small bosses. Hand specimens of the quartz diorite are characterized by medium-grained texture and the presence of hornblende and feldspar, giving a greenish gray color on fresh fracture. Upon weathering, a whitish, sandy soil is produced, in which a few quartz grains can be identified.

The leading primary essential mineral in this rock is plagioclase, with hornblende next in prominence. The feldspar ranges from oligoclase to labradorite, andesine being the most abundant. The hornblende is of the pale-green pleochroic variety, occurring in rectangular plates and irregular broken crystals. Quartz is interstitial and contains many dust-like inclusions and gas bubbles. The texture is that of a medium-grained, crystalline rock. The primary accessory minerals, in the order of their abundance, are: titanite, orthoclase, magnetite, ilmenite and apatite. Alteration has taken place in the minerals to a considerable degree, the feldspars and hornblende having been most affected. The former have given rise to a sericitic aggregate which marks the central portions as well as the borders of the crystals. A saussuritic complex, in which epidote is the prominent constituent, occupies portions of the labradorite crystals. The change in hornblende has resulted in the formation of chlorite, which in some instances is penninite. Titanite has remained unchanged, while the ilmenite has in places passed to leucoxene. Magnetite has given rise to limonitic iron, which in places stains the sections yellowish. The effect on orthoclase has been similar to that on the more acid plagioclase. Quartz is practically unaffected and contains many stout little apatites in perfect condition.

DIORITE

Typical diorite is found at several points in the district, the best exposures being at kilometer 23.9, Ponce-Adjuntas-Arecibo road; four miles up the Portugues River from Ponce, and at kilometer 29.5, Ponce-Adjuntas-Arecibo road, just north of the Ponce District. The forms in which these rocks occur are the same as those of the quartz diorite. The diorites, however, are much more extensive and represent a type closely related to the rock just described. In the field, diorite is marked by a medium to coarse texture, in which feldspar and hornblende are the chief minerals. The greenish black hornblende is more strongly developed in some localities—for example, on the Portugues River—while at kilometer 23.9, Ponce-Arecibo road, feldspar with porphyritic habit is the prominent mineral.

In thin sections the rocks of this group prove to be normal diorites, consisting of plagioclase (andesine and labradorite) and hornblende as primary essential minerals, with a few crystals of oligoclase present. The accessory constituents are ilmenite, titanite, pyrite, pyroxene, magnetite, apatite and biotite. The texture ranges from medium to coarse and in places tends toward ophitic. In a specimen from kilometer 23.9, Ponce-Arecibo road, large crystals of hornblende not only act as "host" for the metallics, but inclose numerous large plagioclase crystals, producing a beautiful ophitic structure. In many instances the plagioclase shows zonal banding, with the successive zones becoming more acid from the center outward. Among the most prominent products of alteration are chlorite, sericite and leucoxene, the chlorite developing from the hornblende and pyroxene and the sericite from the feldspars. Leucoxene is seen filling zones of decomposition along the crystallographic directions of the ilmenite—a feature characteristic of these two mineral associations. Epidote is present as an alteration of hornblende, and pyrite has been changed along the crystal borders to limonite. A small amount of lime carbonate was noted as coming from the hornblende.

TRACHY-ANDESITE

A specimen collected from kilometer 22.2, Ponce-Adjuntas road, proved upon microscopic examination to be a trachy-andesite. Although the areal extent of this type will not permit its differentiation from andesite proper on the geologic map, it is thought best, for the sake of completeness of the petrographic series, to describe it. At the above locality this rock occurs as a small dike and is probably related to the larger dioritic mass which occurs in close proximity. In the field, this rock was classed as an andesite, for its true character is only seen in thin sections. What is true of the andesites as to field characteristics holds also for this rock.

The interesting feature of this specimen is the prominence of orthoclase in a rock which otherwise satisfies the requirements of a hornblende andesite. Oligoclase and andesine are both present, the former being the more abundant. Hornblende of both the light brown and the uralitic varieties is plentiful, the former appearing as basal sections in which the cleavage is well shown, and uralite in more rectangular plates, closely associated with secondary epidote. Orthoclase occurs interstitially as well as in the groundmass, while the plagioclases are arranged in such a manner as to simulate diabasic structure. Magnetite is the chief primary accessory mineral, with apatite and pyrite the only other representatives present. Alteration of hornblende has given rise to epidote and a few patches of lime carbonate closely associated with the epidote. An earthy substance having the appearance of kaolin occupies portions of the feldspars. Magnetite shows practically no alteration.

HORNBLENDE ANDESITE

A typical exposure of this rock is found at the north end of Guayabal reservoir, on the road to Villalba. At this locality the andesite is in the form of a small dike cutting the tuff. The megascopic characteristics of this rock are its greenish white color and the very fine-grained groundmass, in which are set a few feldspar and hornblende phenocrysts. In the field the material looked exceedingly fresh, but thin sections show that alteration of the minerals has progressed to a marked degree.

Although the rock is badly altered, there is still enough left of the primary minerals to determine its original character. Andesine and labradorite, together with hornblende phenocrysts, are set in a dense, fine-grained groundmass made up chiefly of small plagioclase crystals. As accessories, a few oligoclase, pyroxene, magnetite and apatite crystals are seen; the oligoclase and pyroxene being interstitial, while the magnetite occurs chiefly as inclusions in the hornblende. Some grains of magnetite, together with apatite, are distributed throughout the groundmass. The alteration of the feldspars has produced an aggregate of sericite which in places incloses carbonate. Hornblende has altered chiefly to chlorite and carbonate, with some epidote. Apatite is unaffected.

AUGITE ANDESITE

The following localities will serve as representatives of this rock type: Just north of the limestone quarry at Ensenada, "Guanica Central"; one mile west of "Guanica Central"; on the east line of the district, two miles north of the Ponce-Santa Isabel road; kilometer 64.2, Ponce-Peñuelas road; the southeast end of Guayabal reservoir; at kilometer 8.1, Mayaguez-Las Vegas road; and on the west branch of the Canas River, north of the Ponce-Mayaguez road. Augite andesite generally occurs as sills or sheets in the shales and tuffs. In some instances, as, for example, in the tuffs, it is hard to determine the relation, as bedding in this rock is not clearly shown and jointing is so perfect that it might easily be confused with bedding. As seen in the field, rocks of this class vary in color and in their tendency toward porphyritic texture. Specimens one mile west of Ensenada and at the east end of Guayabal reservoir are porphyritic and have a reddish hue, due to the presence of more iron oxide (readily seen in thin sections), while the specimen at the east end of the district, north of kilometer 17.0, Ponce-Santa Isabel road, is dark greenish and shows a stronger porphyritic habit. In all occurrences, pyroxene crystals are visible as phenocrysts, but feldspar cannot always be recognized.

The mineralogy of this rock is that of a normal pyroxene andesite, consisting of plagioclase (andesine, labradorite) and augite as primary essential minerals. The feldspars occur both as phenocrysts and in the groundmass and are marked in many cases by zonal structure. Intergrowths of one feldspar in another are also seen in parts of the thin sections. Augite is developed mainly as idiomorphic crystals with basal and longitudinal sections visible. The minor primary minerals are magnetite, ilmenite and hornblende, the latter being very sparingly represented. The texture varies in some localities, as, for example, just north of the limestone quarry at Ensenada, where there is not the porphyritic habit that is seen in the rock just west of Ensenada. In the former the feldspars have a stubby habit and the contrast between phenocrysts and groundmass is not at all pronounced, while in the latter case the typical porphyritic habit of the andesites is well shown, with feldspars and augite as phenocrysts. The common alteration products are chlorite and iron hydroxide. An example of the former is very well seen in a specimen procured at kilometer 64.2, Ponce-Peñuelas road, where the chlorite is developed from augite, which occurs both in the groundmass and in phenocrysts. Iron hydroxide is developed chiefly from magnetite. Sericite is present as a result of the decomposition of feldspar. Carbonate has been developed both in feldspar and augite. Some of the lime carbonate, however, clearly shows an introduction origin. A small amount of epidote is closely associated with chlorite developed from the pyroxene. Leucoxene is seen to come from ilmenite, which in some slides is rather generously distributed. Native copper, associated with amygdules in a pyroxene andesite, was found on the west branch of the Canas River, just north of the fault between the Tertiary and Cretaceous.

DIABASE

Good exposures of diabase are found at the following points: Kilometer 22.5, Ponce-Adjuntas-Arecibo road; kilometer 3.2, Yauco-Lares road; and kilometer 2.3, Mayaguez-Las Vegas road. Dikes and sills of diabase are not an uncommon feature in the tuff and shale of the Older Series. The above-mentioned localities are a few of the occurrences noted in the field. In size these intrusives vary from small stringers to masses 50 feet or more across, as, for example, the exposure at kilometer 3.2, Yauco-Lares road. The most prominent feature of the hand specimens of diabase is the texture, which ranges from rather coarse diabasic at kilometer 3.2, Yauco-Lares road, to very fine in the rock at kilometer 22.5, Ponce-Adjuntas road. The coarser varieties have a grayish green color, while the finer-grained ones are a dark greenish shade. Outcrops weather to a muddy yellow color, and the soil derived from such material is of a darker hue.

The essential primary minerals of this rock are plagioclase feldspar, of the labradorite and andesine varieties, and augite. The feldspars are arranged in characteristic diabasic fashion, with the augite filling the spaces between. This structure is well seen in the rock from kilometer 2.3, Mayaguez-Las Vegas road. In other instances the diabasic fabric although present, is not so prominent a feature. Of the primary accessories, magnetite and ilmenite deserve first mention. The proportion of these minerals varies. In the sample from kilometer 2.3, Mayaguez-Las Vegas road, ilmenite is much in excess of magnetite, while in the other specimens magnetite appears in greater quantities. Apatite in needle like crystals and stubby cross-sections is also present. Alteration has resulted in the production of chlorite from the pyroxene, a feature well shown by the rock from kilometer 22.5, Ponce-Adjuntas road. Sericitization of the feldspar has advanced in some cases to such a degree as to completely replace the original crystal. Leucoxene developed from ilmenite and iron oxide from magnetite complete the list of alteration products. In the material from the Mayaguez-Las Vegas road, lime carbonate is present in veinlets cutting the other minerals, showing its introduction from outside sources.

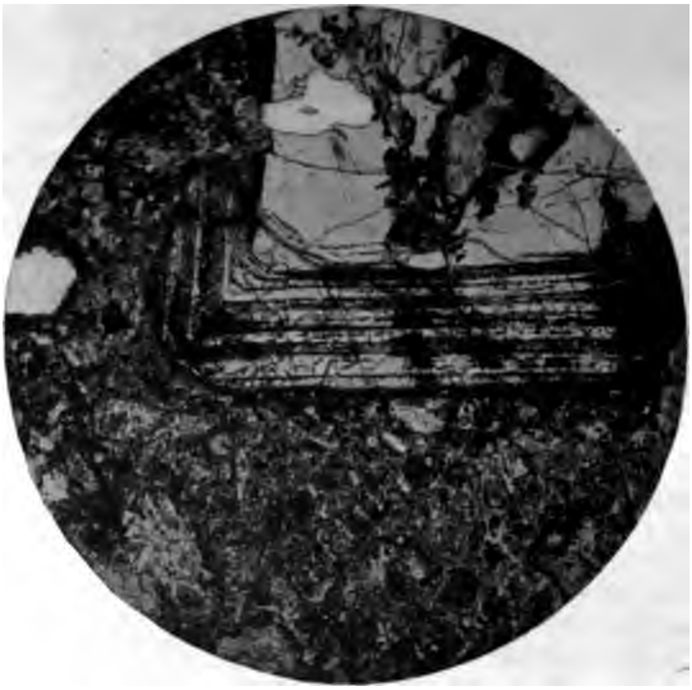

FIG. 6.—*Augite porphyrite showing zoned augite crystal set in fine-grained groundmass* Taken in plain light, magnified about 30 times. K. 8.6, Mayaguez-Consumo-Maricao road.

AUGITE PORPHYRITE

Although porphyritic habit in rocks of the Ponce District is not uncommon, two instances of that type of texture are such striking examples of porphyrite that it is thought best to give them more prominent mention than they might otherwise deserve. The two occurrences are at kilometer 8.6, Mayaguez-Consumo road, and two miles north of kilometer 15.0, on the proposed extension of the Yauco-Lares road. In both localities the augite porphyrite occurs as dikes in the pre-Tertiary shale and tuff. On the Yauco-Lares road the intrusion is much larger than the one on the Mayaguez-Consumo caraterra, being over 75 feet across. This rock is readily identified in the field by the presence of the large, well-formed pyroxene crystals set in the dark greenish, fine-grained groundmass. The specimen from the Mayaguez-Consumo road is of a lighter greenish color and the augite crystals are not so conspicuous.

The most striking petrographic feature of this rock is the porphyritic habit of augite. These large pyroxenes, showing marked zoning, are set in a fine groundmass composed of feldspars and partially decomposed ferro-magnesians. Oligoclase and andesine are present, both in the groundmass and as phenocrysts, with the former more strongly developed in the groundmass. Some glassy matter is also present. Magnetite is prominent as inclusions in the pyroxene and feldspar and as small particles scattered through the finer portion of the thin section. Alteration has progressed farther than would be suspected by an examination of hand specimens. Chlorite is the chief result of this alteration, and has developed from feldspars and ferro-magnesians in the groundmass and from the phenocrysts of these minerals. Cavities which were originally filled with other mineral matter are now occupied by chlorite. Magnetite is partially changed to iron oxide, which has stained portions of the groundmass.

PYROCLASTICS

TUFFS

From many specimens of tuff a set has been selected for microscopic study, which covers the lithologic range of this class of rock. The distribution of the samples chosen is such as to permit comparison in different sections of the district. The thin sections include specimens from the following localities: Kilometer 3.9, Mayaguez-San German road; kilometer 19.8, Ponce-Adjuntas road; at the intersection of Ponce-Adjuntas and Jayuya roads; kilometer 13.7, Ponce-Adjuntas road; kilometer 14.9, Ponce-Adjuntas road; kilometer 12.8, Ponce-Adjuntas road; Guaniquilla

Point; one-quarter of a mile southwest of Lajas; on Jacaguas River wher the road to Villaba makes first crossing; kilometer 31.1, Yauco-Mayague road; kilometer 11.3, Ponce-Adjuntas road; just west of Ensenada; nort three-quarters of a mile from kilometer 72.3, Ponce-Peñuelas road; miles northeast of Maricao; and on the divide ten miles east of Maricao In all the above localities the tuff occurs as massive, faintly bedded material varying greatly in thickness and attitude. On the whole, the tuf shows evidence of fragmental habit, the included rock fragments bein plainly visible. However, in some exposures the rock is thoroughly indurated and does not show evidence of its pyroclastic origin. The colo varies from greenish to reddish tints, with shades of yellow and white It is found on microscopic examination that the colors are due chiefly t the prominence of different secondary mineral products, the reddis varieties being richer in iron oxide, the green in epidote, and the whitis in decomposed feldspar.

The petrographic features of the tuff may be summarized as follows:

(1) The composition is predominantly andesitic, with trachytic, basaltic and glassy varieties present.

(2) Fragmental habit characterizes all the slides, although this featur is more strongly developed in some instances than in others. The fragments show wide range in size, varying from pieces plainly visible in hand specimens to those of microscopic dimensions. Jagged outlines o crystal and rock fragments are characteristic features.

(3) The matrix in which the fragments are set generally contains a quantity of ashy matter, which packs in around the fragments, forming a compact mass.

(4) Many of the individual crystals, as, for example, feldspars and ferro-magnesians, occur as broken fragments.

(5) Included fragments showing spherulitic habit are sometimes present.

(6) Secondary mineral products, including calcite, chlorite and epidote, are strongly developed; the calcite and epidote favoring the feldspars and the chlorite favoring the ferro-magnesians. Where calcite is strongly developed, epidote shows a decrease. All of these minerals also show introduction, especially the calcite and epidote

(7) Magnetite is abundant in some slides and shows alteration to hematite and limonite.

(8) The geologic history of this group of rocks, as far as can be ascertained from the study of thin sections, suggests the following steps:

(*a*) Accumulations of volcanic ejectamenta on land surfaces, with marginal portions of these deposits reworked by water. This marginal reworking accounts for the rudely stratified portions in which the fragments show more or less rounding.

(*b*) Induration involving carbonitization, chloritization and epidotization, which binds some of the rock into a hard, resistive mass.

(*c*) Fracturing and introduction of carbonate, epidote and chlorite.

(*d*) Weathering, producing iron oxides and hydroxides.

SEDIMENTARY ROCKS

SHALE

Specimens from the following localities have been chosen as typical representatives of the range of rock included here under the general head of shale:

(1) Kilometer 5.6, Mayaguez-Consumo-Maricao road.
(2) Kilometer 3.7, Mayaguez-Consumo-Maricao road.
(3) Lapena Point, north side of Mayaguez Bay.
(4) Kilometer 6.+, Mayaguez-San German road.
(5) Kilometer 14.6, Yauco-Lares road.
(6) Kilometer 20.5, Ponce-Adjuntas road.
(7) Kilometer 22.7, Ponce-Adjuntas road.
(8) Kilometer 1.1, Jayuya road.
(9) Kilometer 1.1, Jayuya road.
(10) Kilometer 21.0, Ponce-Adjuntas road.
(11) Intersection of Ponce-Adjuntas and Jayuya road.
(12) Kilometer 16.6, Ponce-Adjuntas road.
(13) East bank Jacaguas River, two miles south of Villalba.
(14) One and three-fourths miles south of San German, on road to Lajas.
(15) One-fourth mile south of San German, on road to Lajas.
(16) Kilometer 7.2, Yauco-Lares road.
(17) Kilometer 111.9, Ponce-Juana Diaz-San Juan road.
(18) One mile north of kilometer 114.0, Ponce-Juana Diaz-San Juan road.
(19) One mile northeast of manganese deposit northeast of Juana Diaz.
(20) Kilometer 112.1, Ponce-Juana Diaz-San Juan road.
(21) One mile northeast of manganese deposit northeast of Juana Diaz.

The most evident field characters of the shale are the bedded and laminated structure and the color. The former is by far the more constant and has an important bearing on the solution of structural relations of the pre-Tertiary formations. The colors exhibited by this class of material have a wide range, including red, bluish gray, black, yellowish and green, with gradation between these colors. Although the color is the first feature which attracts one's attention in the field, especially in the case of the reddish varieties, it must be borne in mind that the colors are the result of alteration and, as will be shown in the petrographic discussion, are dependent upon the decomposition of certain minerals.

The petrography of the shales in the Ponce District may be summarized as follows:

(1) On the basis of composition a general division can be made into those high in carbonate of lime and those high in ashy matter. The lime content is present in the remains of foraminifera shells and as finely disseminated carbonate. When the ashy content is predominant, foraminifera are scarce or entirely absent, and the rock in thin section has the appearance of fine volcanic dust with angular crystals distributed through it. Numbers 1, 2, 3, 4, 6, 9, 10, 11, 12, 15, 17, 19, 20 and 21 are typical ashy shales. Numbers 5, 8, 13, 14 and 16 represent characteristic limy shale. There are gradations between these two extremes, as shown by numbers 7 and 18.

(2) When crystal fragments are large enough to be identified, they are found to be feldspar.

(3) Glass fragments are present in the more ashy shales.

(4) Pyrite, crystalline and massive, is plentiful in numbers 1, 2, 4, 5, 6, 9, 10, 11, 12, 13, 16, 17, 19 and 21.

(5) Magnetite occurs in some slides, but not so extensively as pyrite.

(6) In number 2 an inclusion of coarser-grained material shows lithic fragments of andesite.

(7) The foraminiferal content varies in amount, but is greatest in specimens of the dark bluish gray, strongly bedded rock. A list of the identifiable foraminifera in the different specimens of shale will be given in the paleontological section.

(8) Finely laminated structure is present in numbers 2, 8, 11, 12, 13, 14, 17 and 18. This feature is plainly visible in hand specimens.

(9) The chief alteration has been the oxidation of the iron-bearing minerals, chiefly pyrite. The color of the red and yellowish shale is due to finely distributed earthy hematite and limonite respectively. Leucoxene is present as finely disseminated specks.

(10) The greenish rock, well exposed at kilometers 19.6 and 15.8, Ponce-Adjuntas road, derives its color from the presence of abundant chlorite.

(11) Introduced veinlets of carbonates, chiefly calcite, are prominent in numbers 5 and 14. Many slides show micro faults and fractures.

(12) Cavities left by the removal of mineral matter characterize numbers 1, 3, 6 and 9. These specimens represent the more highly altered and porous rock.

CHERT

The two samples of chert chosen for thin sections are from Lepena Point, on the north side of Mayaguez Bay, and kilometer 6.+, Mayaguez-San German road. At both localities the chert occurs as small, irregular masses in shale and tuff. Hand specimens are grayish to red, with weathered surfaces colored whitish. Some dark red and green chert was found in the vicinity of Villalba. The rock is massive and is traversed by numerous veinlets of quartz.

In thin sections, the rock presents the exceedingly fine-grained quartzose make-up characteristic of that class of material. In some cases the quartz is large enough to be determined optically. Many veinlets of quartz traverse the sections. Pyrite is prominent and hematite in a few grains is identified. Oxidation has produced limonitic substances from the pyrite. This yellowish material is distributed through the rock. Crushing has developed weaknesses which have been filled with quartz veins. A search for radiolaria was made, but none was found in the sections.

SAN JUAN FORMATION

As seen in thin section, the rock is made up chiefly of lime carbonate in more or less rounded grains and irregular masses, through which are distributed angular quartz grains. Feldspar crystals are identified, but are not a prominent constituent of the rock. One crystal of tourmaline was noted. The angularity of the quartz and feldspar crystals is a noticeable feature and shows that the material has not been subject to much wearing action of stream or wind. The quartz and feldspar, together with the tourmaline, which were in all probability derived from the nearby Cretaceous rocks, have been subjected to very little wear before their incorporation in the lime sand. The carbonate of lime is of two types:

(1) Rounded grains.

(2) Crystalline and massive carbonate, filling in around the other minerals. This carbonate of the latter type is responsible for the binding together of the mass.

Metamorphic Rocks

CONTACT METAMORPHICS

Garnet Rock.—The garnet rock described here is located at the iro prospect of Sr. T. Blasini, about four miles north of Ponce, on th Portugues River. This rock occurs as a contact phase of limestone whic has been cut by an intrusive dike. The structural relation of the rock involved are discussed in another section, under Magnetite. The mos noticeable feature of this rock in the field is the knot-like aggregate o reddish brown garnet set in a light greenish, fine-grained mass which i cut by calcite veinlets. Chalcopyrite and pyrite are present in appreciabl amounts.

Pale yellowish brown garnet, determined to be grossularite, makes u approximately 90 per cent of the thin section. The garnet is cut b numerous fractures filled with introduced mineral matter and secondar alteration products. Among the other constituents, named in the orde of their abundance, are lime carbonate, quartz, chlorite, epidote an sulphides. Carbonate, quartz, chlorite and sulphide have been introduced, while epidote is derived from garnet. The order in which th introduced minerals have come in overlaps. All have entered the roc at approximately the same time with the sulphides, slightly in advanc of the others. Carbonate has continued as the last introduction product, with quartz and chlorite following in the order named. The time relations of these introduced minerals is clearly shown in the veinlets which cut the garnet. The sulphides, chalcopyrite and pyrite fill fractures and veinlets in the garnet and are also included in the carbonate.

The chief interest in this rock and the other two, about to be described under the contact metamorphics, is in their relation to the magnetite. A mineral group association which characterizes this rock and which might serve as one example of the result of contact metamorphism o limestone is the following: garnet, calcite, quartz, chlorite, chalcopyrit and pyrite.

Garnetiferous Limestone.—This rock is from the same locality as th garnet rock. The garnetiferous limestone is a contact metamorphic phas of the San German limestone, which at this locality occurs interbedded in the Cretaceous tuff and shale. Fresh material of this class is composed of closely packed calcite and dolomite crystals, with numerous reddish brown garnets dotting the mass. Pyrite cubes and massive chalcopyrite, which shows the iridescent tarnish, are present.

Calcite and dolomite crystals, packed together so closely that crystal outlines have merged one into the other, are the chief constituents of this rock. Calcite is much in excess of dolomite and has the crossed-twin lamellæ well developed. Pyrite cubes and massive chalcopyrite are included in the carbonate and also lie at the junction of several of the calcite and dolomite grains. The garnet is the pale yellowish brown variety, grossularite, in which are quartz and chlorite crystals. Minute dust-like inclusions are common in the carbonates. The rock is very fresh; the sulphides show but little alteration.

Epidote Rock.—The epidote rock is also from the Señor Blasini prospect, on the Portugues River. It occurs as a contact phase of limestone and an igneous intrusion. The nondescript appearance of this rock hardly suggests the beautiful development of epidote which is shown in the thin sections. Veinlets of epidote cutting the dark crystalline mass are the most noticeable feature in hand specimens. Dark brown garnet has a very slight development and a few sulphides can be identified.

In thin sections epidote and quartz are seen to be the chief minerals present. The time relation of these minerals is practically the same. Both act as "host" and "guest." Where "host," the minerals occupy large, irregular patches; and where "guest," they are present as small inclusions. Actinolite is identified as inclusions both in quartz and epidote. Patches of lime carbonate with chalcopyrite and pyrite inclusions are identified. The sulphides have been slightly attacked by weathering, but otherwise the rock is quite fresh. The mineral association is epidote, quartz, actinolite, calcite, chalcopyrite and pyrite.

KATAMORPHIC ROCK

Serpentine.—The distribution of serpentine rock can be seen on the Geologic Map. Its most extensive development is in the region north of Sabana Grande and southeast of Mayaguez. Specimens chosen for microscopic examination are from one-quarter of a mile south of the Reform School, southwest of Mayaguez; north of Sabana Grande five miles; from kilometer 41.7, Yauco-Mayaguez road. At the first and last locality mentioned this rock occurs in the form of dikes, but in the region north of Sabana Grande it takes the shape of a large, irregularly outlined intrusive mass in the Cretaceous formations. The exposures of serpentine are most frequently dark green to nearly black, with light shades of green characteristic of the more altered material. Some exposures are coated with a whitish alteration product, while in other instances iron stains the outcrop yellowish or reddish. The only minerals recognizable in hand specimens are pyroxenes and chrysotile, the latter forming small veinlets cutting the mass, and the former as phenocrysts, best seen on freshly broken surfaces. More thoroughly serpentinized exposures have a characteristic oily appearance and soapy feeling. In the specimens south of the Reform School, pyroxene crystals have weathered in relief, giving the surface a rough appearance. Much of the rock is strongly jointed and sheared and slumps where exposed in steep banks.

Microscopic examination shows the serpentine to be derived from peridotite. Enstatite and olivine are the most abundant primary minerals, the former occurring generally as large, lath-shaped crystals showing varying stages of alteration to serpentine, and the olivine is distributed as individuals among the pyroxene and as inclusions in the enstatite. Residual cores of olivine in serpentine are prominent in portions of the slides. Bronzite and diopside are present as scattered individuals. Olivine is more abundant in the rock north of Sabana Grande and south of the Reform School. Magnetite and chromite are plentiful, much of the magnetite being secondary after olivine. Alteration has produced antigorite and chrysotile from the olivine. Cores of olivine surrounded by serpentine characterize sections where this mineral is present. At times only the outline of the former olivine crystal remains, the center having been filled with a serpentinous product. Veinlets of chrysotile cut portions of the slides. The decomposition of olivine gives rise to magnetite, which in turn has furnished the iron oxide and hydroxide which appear as stainings. Enstatite has been changed to bastite, which replaces entire crystals of the former. In other instances the attack has progressed only so far as to produce a change on the border and along lines of weakness in the pyroxene. The lamellar structure of the enstatite is inherited by the bastite, giving a structure easily distinguished from the core-like pattern of the decomposed olivine.

PALEONTOLOGY

Introductory Statement

The paleontological material collected during the survey of the Ponce District lends itself to the following general classification:

(1) Post-Tertiary fossils found in elevated gravel, sand and silt of former embayments; shells on the elevated wave-cut terraces along the coast and in the surface layers of playas.

(2) Fossils from the Tertiary limestone and marl along the south coast.

(3) A few forms of upper Cretaceous age from the limestone and limy shale of the Older Series of Berkey.

In this report one new species and one variety are listed. The paleontological publications in the bibliography contain descriptions and illustrations of the other species here identified. The post-Tertiary fossils, all of living species, are found in perfect state of preservation. Details as to location and occurrence of these forms have been given under the discussion of terraces. The Tertiary formation has yielded a variety of forms with representatives from the lower and upper Oligocene. In the discussion of the lithology of these beds reference has been made to the distribution of the fossils and the lithologic character of the rock in which they are found. Upper Cretaceous *Radiolites* sp., *Actæonella* sp. and *Hemiaster berkeyi* n. sp. have been identified from the formations making up the older rocks in the district. The first two forms have been determined by Dr. T. W. Stanton, of the United States Geological Survey, and the *Hemiaster berkeyi* by Dr. R. T. Jackson. Details of the formations in which these forms occur have been discussed heretofore.

POST-TERTIARY FOSSILS

Post-Tertiary fossils were found in the elevated terrace gravel, sand and silt and in the estuarine deposits on the floodplains of some of the rivers along the south and west coasts. The list of forms identified are:

Conus sp. like *Conus portoricanus*,
Strombus pugilis,
Lucina jamaicensis,
Lucina tigrina,
Arca tuberculosa,
Byssoarca ziebra,
Murex elongatus,
Arca rhombea,
Turritella imbricata,
Pecten nucleus,
Venus cancellata.
Ostrea sp.,
Strombus accipitrinua,
Fissurella nodosa,
Turbo pica,
Manicina sp.,
Cerrithium litteratum,
Pterna sp.

TERTIARY FOSSILS

The Tertiary fossils from the Ponce formation have been identified as forms belonging to the Oligocene. The following is a list of those determined:

Clypeaster rosaceus, Lamark (Fig. 7),
Pecten sp.,

Phacoides sp.,
Strombus sp.,
Bulla sp.,
Teredo incrassata, Gabb,
Arca sp.,
Spondylus sp.,
Lucina sp.,
Leda sp.,
Corbula sp.,

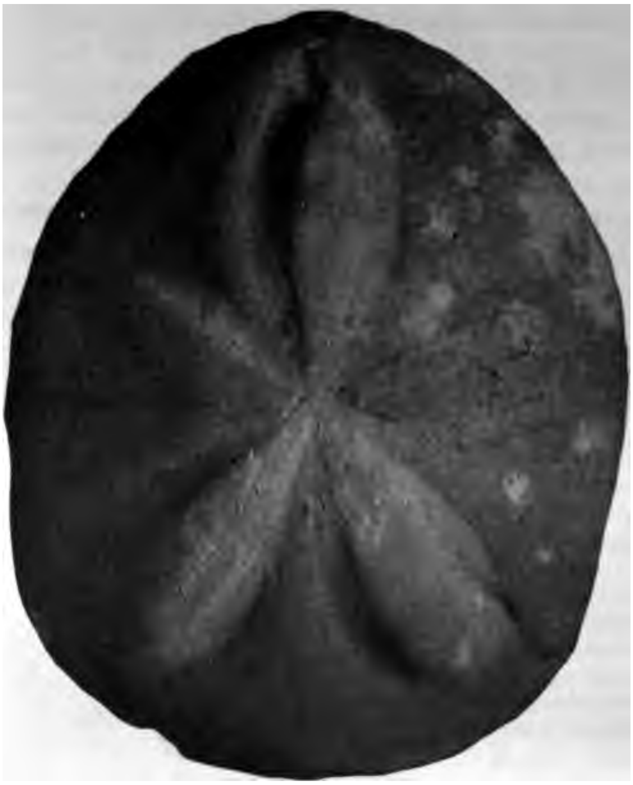

FIG. 7.—*Clypeaster rosaceus,* Lamark

Orbitolites complanata, Lamark,
Nummulites sp.,
Arca sp.,
Cardium sp.,
Pecten chipolanus, Dall,
Ensis sp.,
Pecten sp.,
Amphistigina lessoni, d'Orbigny,
Cryprœa sp.,

Natica sp.,
Amauropsis sp.,
Astarte sp.,
Cardium sp.,
Turritella halensis, Dall,
Turritella halensis alpha, new var.,
Cythara sp.,
Fasciolaria sp.,
Pecten sp.,
Laganum sp.,
Orbitoides mantelli, Morton,
Leaf fragments.

A new variety of ***Turritella halensis*** var. ***alpha*** has been found, associated with *T. halensis*. Its variation from *halensis* is given below in the description of the form.

Turritella halensis var. alpha

This form differs from *T. halensis* in having the secondary spirals less prominent and also by the lesser prominence of the primary spirals on the main surface of the whorl. Only the upper two spirals are strongly developed, the third one being very weak, thus giving a distinction to that portion of the whorl. The lowér two spirals are pronounced and become confluent into a nearly uniform ridge on the later whorls. The beading is well marked on the upper two spirals, but obsolete on the others. There may be a slight change in the surface of the shell, due to solution; but the general characters could not have been affected to the extent shown.

Locality.—Jacaguas River, northeast of Ponce; occurs in the marly beds above the *Orbitoides mantelli*.

CRETACEOUS FOSSILS

The following fossils have been collected from the San German limestone *Radiolites* sp. (Upper Cretaceous) and *Actæonella* sp. (Upper Cretaceous). The *Radiolites* sp. is abundant in large and small fragments. It can be easily identified on weathered surfaces by the mesh-like structure produced by weathering of transverse sections. The *Actæonella* sp., together with the *Radiolites* sp., serves as an index of these limestones.

From the Cretaceous shale and limestone the following foraminifera have been identified:

(1) Shale just south of Melones Point. These beds are the westward extension of the shale at Ensenada, which carries *Hemiaster berkeyi*.

Textularia sp.,
Pulvinulina sp.,
Globigerina cretacea, d'Orbigny,
Orbulina universa, d'Orbigny,
Globigerina bulloides, d'Orbigny.

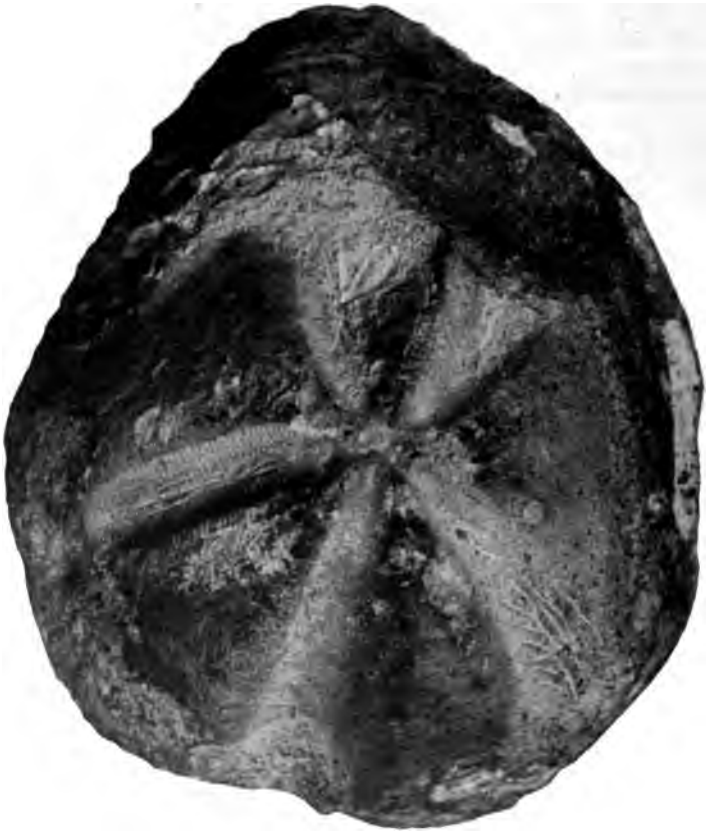

FIG. 8.—*Hemiaster berkeyi* n. sp., Jackson. × 3/2

(2) Guayabal limestone, one mile east of the manganese deposit nor of Juana Diaz.

Globigerina sp.
Much fragmental foraminifera not identifiable.

(3) Ensenada shale.

A large amount of fragmental foraminifera.

The description of the new species of *Hemiaster* (Fig. 8) found in th shale has been furnished by Dr. R. T. Jackson, who states that its affinities are with the Cretaceous. His description follows:

> Test large, cordiform, high, subconical, rounded below, from the highest point of the test dorsally sloping anteriorly, posteriorly and laterally to the ambitus. Ambulacra petaloid, wide, in deep broad furrows. The anterior ambulacrum III is narrower than the others and lies in a shallow furrow which reaches to the ambitus. Ambulacra II and IV, the anterior pair, are widely divergent at an angle of about 95° to each other and are in grooves which extend nearly to the ambitus. They measure 30 millimeters in length. The posterior ambulacra I and V lie in grooves and are narrower and much shorter than the anterior pair, measuring about 18 millimeters in length. The pores in the paired ambulacra are at the ends of narrow slit-like grooves. The interambulacra are narrow and elevated dorsally. The apical disc is very close to median in position, perhaps actually median, but from imperfections posteriorly exact measurement in the antero-posterior axis cannot be made. The apical disc is quite well preserved and shows the four genital plates with large perforations; the madreporite is of medium size, meeting but not separating the other genitals. Oculars I and V are in contact on account of the absence of genital V, as is characteristic of the genus. From imperfections the peristome and perisproct are not preserved. Small perforate tubules with subtubules are scattered over the test, somewhat distantly, and small granules thickly cover the spaces between the larger tubules. The specimen measures 40 millimeters in height, and this is a close approximation to the real height, though, if not worn ventrally, it would be slightly higher. It measures about 65 millimeters in length and 65 millimeters in width. The specimen is very much larger than any other fossil species found in the West Indies. It differs also in its shape from any known North American species.
>
> At the request of the collector, Mr. Graham John Mitchell, this species is named in honor of Prof. Charles P. Berkey, of Columbia University.

GEOLOGIC HISTORY

INTRODUCTORY STATEMENT

In an historical summary of the geology of Porto Rico, Berkey (1915, p. 60) noted the following steps:

> (1) A long geologic period of volcanic activity, accompanied by marginal attempts at assorting of fragmental and detrital material of organic accumulations, disturbed from time to time by renewed or extended igneous activity.
>
> (2) A dying out of volcanic energy, greater stability of the mass with respect to elevation and subsidence, and erosional attack continued long enough to result in extended planation and partial baseleveling, with final extensive submergence.
>
> (3) The development of an unconformable overlying series of shales, reef limestone and related deposits, chiefly of organic origin, brought to an end by final re-emergence.

(4) The development of present surface features under stream erosion and marine marginal attack, with modifications arising from oscillation of level.

These, with a few additions, are essentially the events in geological history of the Ponce District, a summary of which is given below.

CRETACEOUS ROCK DEPOSITION

The oldest geological record in the Ponce District is represented by a series of interbedded tuff, shale and limestone beds which comprise the Cretaceous formation. These rocks represent a period of volcanic activity in the form of explosive eruptions, with periods of lesser activity marked by the development of limestone and foraminiferal shales. The greater part of the tuff was deposited upon land with the sea encroaching upon the borders of this material and reworking areas to form shale. Heavy showers of volcanic dust contributed to the supply of material for the shales found interbedded in the tuff. That there were intervals during this volcanic period when organisms could exist in abundance is shown by the *Radiolites* sp., which formed reef-like masses, now represented by the interbedded San German and Guayabal limestone. Foraminiferal shales also accumulated in these less-disturbed intervals. In some instances previously formed rocks were broken up by the eruptions and redeposited to form such rock as the Coama tuff limestone. The Guayabal limestone represents a period of limestone formation higher than the San German and Coama tuff limestones, but in the same geological epoch, namely, Upper Cretaceous. The latest Cretaceous record, as shown by the rock in the district, is that of renewed volcanic activity with the formation of tuff.

DEFORMATION AND INTRUSION

Toward the close of the Cretaceous the region was subjected to dynamic disturbances which resulted in a pronounced folding of the formations. Accompanying this folding came the igneous intrusions of diorite, andesite, diabase, peridotite, etc. It has not been possible, from the date secured, to work out the sequence of these intrusions. Their effect has been to produce baking, which is exhibited by the shale, and to form mineral deposits, as, for example, the magnetite on the Portugues River.

EROSION OF CRETACEOUS

Toward the close of the Cretaceous there was uplift of the region, followed by a period of erosion long enough to wear down the exposed rocks to a partial plain, designated as the Eocene peneplain (Berkey, 1915, p.

41). This old surface is probably represented in the Ponce District by the mesas southeast of Mayaguez.

TERTIARY SEDIMENTATION

The next event of which there is a record is found in the deposition of lower Oligocene shaly and marly limestones. The base of the Tertiary in the Ponce District has been obliterated by faulting, which has also destroyed the normal relations of the Tertiary and Cretaceous beds. However, as stated elsewhere in this report, the marked unconformity existing on the north side of the island between the formations of these two geologic epochs was also undoubtedly present on the south side.

The lowest Tertiary is represented by the rocks exposed along the Jacaguas River northwest of Juana Diaz. The sandy character of the marly and shaly limestone and the presence of many fragmental fossils and plant remains indicate shallow-water deposition. The change from this near-shore type of deposition to somewhat deeper water is indicated by the passage of these lower beds up into the chalky limestone of the upper Ponce formation. The waters in which these higher beds were laid down were much quieter and freer from sand and mud. Toward the top of the Oligocene (Upper Oligocene) the conditions became suitable for coral growth, as is indicated by the masses of coral heads imbedded in the chalky limestone. Whether or not Tertiary beds higher than the Upper Oligocene were deposited in the district cannot be determined, as the next record of deposition above the Oligocene is in the San Juan formation of Pleistocene age.

DEFORMATION AND UPLIFT OF TERTIARY

Toward the close of Tertiary deposition the region was again uplifted, accompanied by dynamic disturbances which produced gentle folds whose axes trend north-south and east-west. The fault between these rocks and the Cretaceous probably started its first movement at that time and reached its present amount of displacement before the close of the period of erosion which followed.

EROSION OF TERTIARY

The next event was the dissection of the Tertiary Coastal Plain and stripping of these deposits from much of the area formerly covered. The Complex Mountain Province thus uncovered or still exposed continued to undergo erosion and to contribute to the supply of waste which is now partially represented by the playa deposits. The larger valleys—for example, Guanajibo and Yauco-Boqueron—were cut during this period.

Submergence with Marine Terrace-cutting and Formation of San Juan Formation

The submergence which followed the main Tertiary erosion allowed the sea to extend up the river valleys, where it laid down gravel, sand and silt and formed the present elevated estuarine deposits. It was during this period that the highest marginal terraces were cut. The highest recorded terrace is approximately 200 feet, but the amount of submergence may have been somewhat greater than that. During this submergence the fossiliferous San Juan dune sand was consolidated and a conglomerate consisting chiefly of pebbles derived from the Cretaceous rocks was deposited upon it.

Emergence

From that time the movement appears to have been one of periodic uplift, finally reaching the present land-level. These uplifts resulted in the terracing both of the estuarine and inland floodplain deposits and in the cutting of the lower terrace levels on the formations along the south and west coasts.

ECONOMIC GEOLOGY

General Statement

The metallic mineral deposits in the Ponce District are confined to the Cretaceous rocks. The most extensive deposit is the limonitic iron, which is associated with serpentine rock. Manganese is the next in extent and is confined to the Guayabal limestone north of Juana Diaz. Magnetite is found along the upper Portugues River north of Ponce, where it has been formed along the contact between limestone and an igneous intrusive. No deposit of copper was found, although greenish stained andesite in which small particles of native copper are present outcrops north of kilometer 72.+, Ponce-Peñuelas road.

Among the material classed as non-metallics are salt, building stone, road-metal, cement material and petroleum. In the following pages all of the above resources are treated in as much detail as the individual cases seem to warrant.

Manganese

The only locality in the district where a deposit of manganese was found is north of Juana Diaz, where it occurs in the Guayabal limestone.

The property is owned by a company of which Deputy United States Marshal George Trautman, of Ponce, is the local representative. Several pits have been opened and a quantity of ore extracted. The method of working is as follows: The good ore is removed from the pits by means of pick and shovel. It is then sorted by hand, sacked and carried by pack-train to the military road, a distance of about three miles, where ox-carts transport it to the Ponce Playa for shipment.

The ore occurs as irregular-shaped masses along crushed and jointed zones in the Guayabal limestone. The size of the pits from which ore has been removed averages about 20 feet wide and 30 feet deep. The ore minerals are psilomelane and pyrolusite. The former is the more abundant and has the characteristic botryoidal form. It also occurs in layers with the pyrolusite, which shows short, indistinct crystals. Much of the manganese is massive black psilomelane, some of which is carried down the hillside by surface water, leaving a black trail behind. Calcite, crystalline and in banded form, is intermixed with the manganese.

The manganese owes its origin to secondary processes. The mode of occurrence of the oxides eliminates the possibility of a primary origin of these minerals in the limestone. The presence of the ore in pocket-like bodies of no great extent laterally or in depth and the location of such bodies in crushed and jointed zones indicate a concentration of the oxides by surface waters moving through these channels in the limestone. Such fracture zones would offer an easy course to manganese-bearing solutions. The original source of the manganese is not entirely evident. A microscopic study of the limestone country rock disclosed no primary manganese minerals or other minerals from which the oxides might be derived. A possible source of the manganese would be the jasper, which occurs as irregular masses in the limestone and which is found coated with manganese oxides. These jasper masses are not always found in direct association with the ore, but in most cases are only a short distance away. In one instance reddish jasper was found with manganese oxides coating the jasper and replacing it. From the field evidence, it appears that the jasper was the original source of the ore where the manganese minerals were probably present as rhodonite and rhodochrosite. Subsequent leaching, in the process of weathering concentrated the psilomelane and pyrolusite in the crushed zones in the limestone. Fragments of limestone are found imbedded in the manganese oxides which have partially replaced the country rock. In thin sections the oxides can be seen replacing the fragmental *Radiolites* and foraminiferal remains and cutting the wall rock in a network of veinlets.

Harder (1910) discusses the manganese ores in the Franciscan jasper of California and states that "the original source of the ore is the jasp itself." Further search for manganese in the Ponce District should confined to the limestones, especially the Guayabal formation, and tho portions closely associated with the jasper should receive first attentio

MAGNETITE

A prospect of magnetite along the Portugues River north of Ponce w visited in company with the owner, Señor T. Blasini, of Ponce. Th property is known as Tibes and is about four miles north of Ponce. N development work had been done up to the time of the writer's visit, wit the exception of a few shallow pits, which were not sufficient to determin the extent of mineralization.

From an examination of the few openings made, it can be seen that th ore owes its origin to contact metamorphic action of a felsitic dike cutting the San German limestone. The intrusive is so strongly modifie that its original character cannot be determined. However, it has th appearance of an andesite.

The magnetite, with a little pyrite and chalcopyrite, is intimately associated with garnet (grossularite). The ore, as far as could be determine from the openings, occurs in irregular replacements along the limeston igneous contact. The limestone at this point dips with a steep angle an is cut by the felsite dike, which has a nearly horizontal attitude. Th property is worthy of further prospecting to determine the full extent o the ore.

LIMONITE

The most important limonite deposit in the district, on the Mayague mesa, has been discussed in a very comprehensive paper by Fettke an Hubbard (1918). Since this paper may not reach all those interested i this iron deposit, it is proposed to summarize here the results of Fettk and Hubbard's study and to add additional localities for this type of ore In regard to the distribution and mode of occurrence of the limonite Fettke and Hubbard state:

> The limonite occurs as a mantle of brown to reddish brown soil overlyin the top of the mesa and extending part way down its sides. Over most of th steep northern and southern flanks, however, it is absent, the underlying serpentine rock coming to the surface here. The material does not furnish a ver fertile soil, so that vegetation on the mesa is scanty, as compared with th luxuriant growth of tropical plants covering the adjoining hills. Over mos of the mesa the total thickness of the limonite is not exposed, and, as this can not be determined without drilling, a few measurements only were obtaine during the hasty reconnaissance made by the writers.

> The gradation from weathered serpentine into limonite, wherever the contact is exposed, is a sharp one. As a rule, the serpentine just beneath the iron ore has been altered from the dark green, dense rock, already described, to a light yellowish green, soft, porous mass, abundantly stained by brown hydrated oxide of iron. The iron ore itself usually has a reddish brown color, but intervening between it and the altered serpentine there are, in most cases at least a few inches of brown material.

The character of the iron ore is summarized by them as follows:

> Most of the limonite deposit consists of a loose, porous, earthy mass varying in color from light yellowish to a dark reddish brown. Usually the red portions occur nearest the surface, while the brown rest upon the serpentine. The relative percentage of iron in the ore cannot, however, be determined from the color, as frequently the brown varieties contain a higher percentage of ferric oxide than the darker red. The shade of color is undoubtedly due to the degree of dehydration of the ferric oxide. Toward the surface the limonite tends to lose its combined water and gradually passes into less hydrated forms of ferric oxide and finally to hematite.
>
> In addition to the loose earthy material, numerous boulders and masses of hard ore occur scattered over the limonite area. These boulders retain the porous structure of the soft ore, but contain little veinlets running in all directions and filled with the botryoidal form of limonite with varnish-like luster. These boulders range in diameter from a few inches up to several feet: apparently they have been washed out of the upper layers of loose material.
>
> A thin section from such a boulder, under the microscope, showed that the hydrated iron oxide is present in two forms, cryptocrystalline and amorphous. The former variety retains the structure of the serpentine, while the amorphous has been deposited afterward in little veinlets running in every direction throughout the former; these show a banded structure. Small grains of magnetite and chromite appear here and there, just as in the serpentine rock.

The conclusions of these authors upon the origin of the limonite is quoted below:

> From the preceding description, it is seen that the limonite deposits of the Mayaguez mesa are almost exactly similar to those in northeastern Cuba, which have been studied by a number of geologists, all of whom have agreed that they are residual in origin, being derived from the underlying serpentine by the weathering of this rock.
>
> It will, therefore, be sufficient to summarize briefly here the main lines of evidence that point to the residual origin of the limonite. These have already been ably discussed by the geologists who have described the Cuban deposits.
>
> The close association of the limonite and the serpentine points strongly to such mode of origin: where other rocks lower in iron underlie the surface, the soils are relatively poorer in iron oxides. That the original structure and texture of the serpentine can still be detected in some of the hard ore furnishes almost indisputable evidence that the limonite has been derived from it in this manner. The irregular contact of the iron ore with the underlying serpentine is also characteristic of residual deposits derived from underlying rocks by

the process of weathering. Likewise, the extremely porous structure of the limonite, where slumping has not occurred, shows that it has been formed by a leaching process in which the more soluble constituents have been dissolved by circulating waters, leaving the less soluble constituents behind. The relatively high percentage of chromite in the ore also indicates the same origin. Chromite is a relatively insoluble mineral, and therefore remains behind in the residual soils.

Finally, a comparison of the analyses of the serpentine and the limonite furnishes further evidence for supposing that the latter was derived from the former (Table 6).

TABLE 6.—*Comparative Composition of Serpentine and Limonite*

	Serpentine, per cent.	Limonite, per cent.
SiO_2	38.41	2.44
Al_2O_3	4.96	20.21
Fe_2O_3	6.32	57.69
FeO	1.27	0.85
MgO	33.32	0.61
CaO	0.04	trace
Na_2O	0.27	not det.
K_2O	0.10	not det.
H_2O at 110° C	0.83	1.09
H_2O + ignition	13.40	14.96
TiO_2	0.08	0.26
NiO	0.72	1.00
Cr_2O_3	0.42	1.57
	100.14	100.68

The only further information which might be added is to note other, less extensive occurrences of the same type of ore as that found in the Mayaguez mesa. The writer has gone over the area examined by Fettke and Hubbard, and has also studied the serpentine to the east of the mesa and at other points in the Ponce District. The limonitic iron was found at a number of localities in the mass of serpentine, the western end of which forms the Mayaguez mesa. The deposits are very irregularly distributed, much of the serpentine showing only iron stains. The other locality worthy of mention is at the Reform School southwest of Mayaguez, where shallow pits have been sunk. The limonitic soil at this point is filled with shiny nodules of brown iron ore.

COPPER

An unsuccessful attempt was made to locate a reported copper deposit north of San German. The rock in this region is chiefly serpentine, and, although places showing copper staining were found, no deposit was encountered. It is possible that ore may occur here similar to that found on the Pacific coast (Butler and Mitchell, 1916). Copper in the form of small particles was found in andesite north of kilometer 72.+, Ponce-Peñuelas road, near the fault contact. The mineral is very sparsely distributed in the andesite, being associated with the filling of amygdules. Weathering has produced greenish copper stains coating the surface of the rock.

SALT

Salt is derived by solar evaporation of sea water in artificial salt pans along the south and southwest coasts, at four different places. The largest of these is the Salinas de Cabo Rojo, in the extreme southwest corner of the district, near Cape Rojo. A memorandum of the Salinas de Cabo Rojo, furnished by Señor Arturo Bravo, of San Juan, is included here:

> The so-called Salinas de Cabo Rojo are situated on the southwest point of this island, about where Morrillos Lighthouse is located.
>
> The salt production is divided into three sections, viz: "Fraternidad" on the south, between Morrillos and Punta Aguila; "Candelaria" on the west, between Punta Aguila and Punta de Hicacos; and the "Corozo," between Punta de Hicacos and Punta de Penones.
>
> The salt is obtained by solar evaporation.
>
> There are two large ponds, one natural and the other artificial, which receive the sea water through ditches. From these ponds, by means of wooden canals, the water is pumped into the crystallizers, wind power with five mills being used. The salt is taken with wheelbarrows from the crystallizers and stored near by in pyramid piles, and when dried is carried to the shore in small open wagons, driven by oxen, through rails in some instances, and in others with common ox-carts, which unload into lighters at a small wharf, and the lighters take the salt to the vessels.
>
> The number of crystallizers amounts to 41, and their capacity of salt varies from 25 to 100 tons each, averaging in all about 3500 tons. In ordinary weather conditions through the year, these crystallizers condense four times, showing a total production of 14,000 tons. There is room for building more crystallizers at a very small cost, to duplicate the production, and with some further improvements it might yet considerably increase.
>
> Exceptional unfavorable weather is usually experienced every ten or twelve years, and we had to encounter with such contingency in 1913, when the yield amounted only to 2870 tons.
>
> Wages are paid at the rate of 50 cents per day for any ordinary work, but the labor on shore for shipping is paid by the weight, at the rate of one cent per hundred pounds. The labor for gathering the salt in the crystallizers, carting it out and piling is paid at 4 cents fanega. Shipping by lighters is paid at $2.00 per hundred fanegas. Each fanega is equivalent to about 300 pounds or over, according to the weight of the salt.
>
> Our salt is well known in different American markets and particularly so in Boston. During the years 1910, 1911 and 1912 eighteen cargoes were shipped

to the United States in vessels from 550 to 1750 loading tons capacity, but sai shipments have been stopped since the duty on foreign salt was taken of according to the Underwood tariff.

The island's consumption is estimated at from 11,000 to 12,500 tons per yea of which we furnish about 5000, the other smaller salt places here about 500 and the remainder is imported from Curacao. These importations from Curacao have been considerably increased since foreign salt is coming in free o duty, but we hardly think the competition with home production may be muc longer maintained in spite of the exceedingly cheap production in the neighboring island, due to small wages and more reduced expenses prevailing there

Our property consists of about 1853 cuerdas (each cuerda approximately on acre) of land, about one-third of which covers the extension required for th salt manipulation.

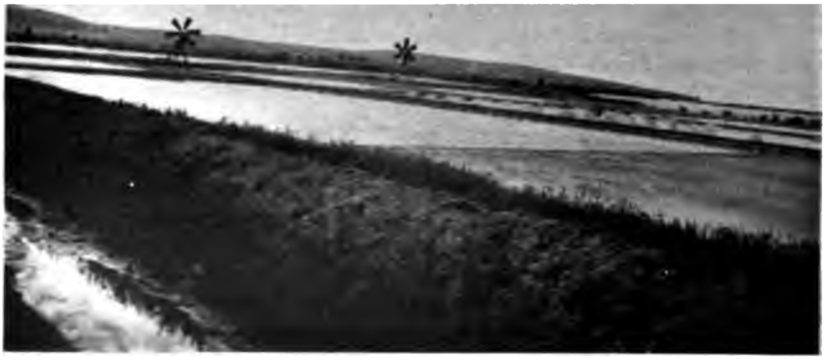

FIG. 9. *"Montalva" Salina, west of Guanica, on south coast*

Other places producing salt are the so-called Boqueron, near the Salina de Cabo Rojo, which yields nearly 1000 tons annually; Guanica, on th south coast, producing 3000 tons, and Montalva (Fig. 9), near Guanica 1500 tons. The methods used in these smaller salinas is practically th same as that employed at the Salinas de Cabo Rojo.

BUILDING STONE

Only three formations in the district lend themselves to building purposes. These are the Coama tuff limestone, Guayabal limestone, an portions of the Ponce chalky limestone. All of these stones have bee used, with the exception of the Guayabal limestone, which, though i appears to be suitable for interior marble-work, has not, to the writer' knowledge, been employed for such a purpose.

The Coama tuff limestone has been used in some buildings, notably in Ponce, where it has also been employed in curb construction. The striking lithologic character of the rock makes it a unique building stone. The Ponce chalky limestone has also been used in some of the older buildings in Ponce. It has served very well in the smaller structures. The Guayabal limestone north of Juana Diaz offers a considerable supply of material suitable for interior decorative purposes. The rock takes a good polish, presenting an attractive cream-colored surface. Joints are prominent in much of the material, but field examination shows that blocks of considerable size, free from joints, can be secured.

ROAD-METAL

An abundance of first-class road-metal can be found in nearly all parts of the district. The rock used for the excellent macadam road depends in a large measure upon the local supply. Among the varieties in use are San German limestone, tuff of all varieties, shale, igneous rocks and the white Ponce chalky limestone. Of the above, the best materials are the San German limestone, highly indurated tuff, foraminiferal shale and igneous rocks.

CEMENT MATERIAL

An abundance of cement material is found in the shales and limestones which are so prominently developed in the area from Peñuelas westward. However, the lack of a local fuel supply on the island makes the possibility of developing such an industry a doubtful one.

PETROLEUM

The only locality where conditions appear favorable to the accumulation of oil is in the region west of Juana Diaz, in the sandy, shaly and marly beds of the lower part of the Ponce formation. An examination of these beds disclosed no indication of the presence of oil, although the structure is such that oil could accumulate. The sandy portions of the beds are capable of acting as a reservoir, with the more shaly material serving as capping strata. If further investigation of oil possibilities is made in Porto Rico, these beds should receive attention, though from the evidence secured during the present survey there is nothing to justify the belief that petroleum will be found in this district.

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SCIENTIFIC SURVEY

OF

Porto Rico and the Virgin Islands

VOLUME I—Part 4

The Physiography of Porto Rico—*A. K. Lobeck*

NEW YORK:
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THE PHYSIOGRAPHY OF PORTO RICO

BY ARMIN K. LOBECK

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INTRODUCTION

Porto Rico, the easternmost of the larger Antilles, is a rugged mountain mass trending east and west for a distance of over one hundred miles, flanked by uplifted limestone plateaus on its north and south sides. It lies well within the tropics, in the latitude of 18 degrees north, and is subject to the influence of the steady northeast trades. The persistence and regularity of the trade winds can not fail to excite the notice of the northerner who is accustomed to more variable conditions. Their effect upon the island is pronounced and shows itself in the marked contrast in precipitation between the north and south sides. An elevation of about 2000 feet prevails throughout much of Porto Rico, so that the trades are forced to rise and precipitate their moisture over the northern two-thirds of the island (Fig. 1). Out of the brilliant sky dense cloud masses form with great rapidity over the uplands and several downpours may be expected during the day throughout most of the year. But when the winds reach the lower lands of the southern coast they have not only lost a large part of their moisture, but in their downward journey they have been transformed into drying winds, with the result that this whole coastal area is almost barren and parts of it experience months, or even years, without rainfall. Irrigation is there essential for the cultivation of large crops, and in the southwestern corner of the island, where there occur the longest periods of drought, considerable areas are densely covered with cactus. Over the rainy windward portion of Porto Rico streams are numerous and always flowing. In the dry leeward portion, river courses are intermittent and coalescing alluvial fans fringe the shallow coast for many miles. The trade winds are also responsible for the strong waves of the north coast, which have thrown up beaches and bars and have developed a magnificent stretch of cliffs. This is in marked contrast with the southern coast, where there is almost no disturbance to the water and mangrove swamps abound.

The shape of Porto Rico in general is that of a rectangle, with a long east-and-west dimension of 110 miles and a north-south width of 35 miles, giving the island an area three-fourths that of the state of Connecticut.

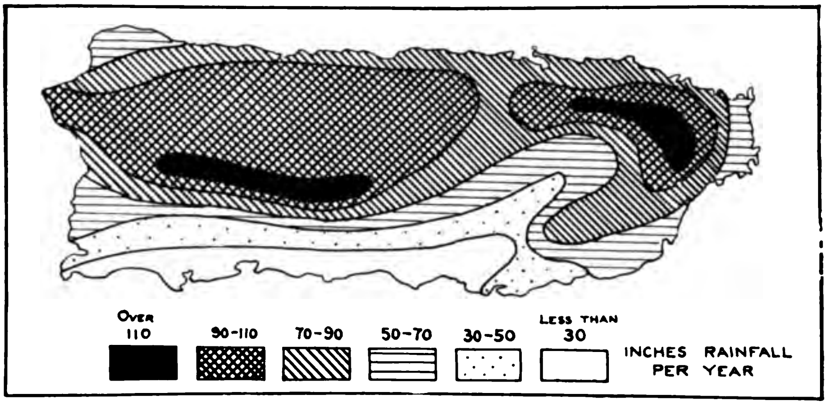


Fig. 1.—*Map showing the average annual rainfall in Porto Rico*

The population of Porto Rico is approximately half that of Manhattan Island, roughly between 1,200,000 and 1,250,000 people. It is, in fact, one of the most densely inhabited regions of the globe. Although there are some 65 to 70 villages on Porto Rico, the people are predominately rural and are scattered quite uniformly over the entire island, even throughout its most rugged portions. The largest three cities—San Juan, Ponce, and Mayaguez—have populations from 35,000 to 50,000. Many of the smaller villages contain less than 1000 people, but most of them average between 1000 and 2000. The towns are invariably built compactly around the public square or plaza which the cathedral fronts on the east. The only extensive part of the island not settled is the area comprised in the Luquillo National Forest, which covers the higher portions of the Luquillo Mountains.

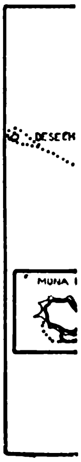
Coffee, tobacco, sugar, and citrus fruits make up almost the entire agricultural output of Porto Rico. Coffee-raising is confined to the upland areas, tobacco is the important product of the Caguas and Cayey valleys in the east, sugar is the great crop on the extensive flood plains and coastal regions, and the raising of grape-fruit and oranges has been developed in the hills along the north coast west of San Juan. In spite of its splendid possibilities the island is far from being self-sustaining in the matter of food, and the great mass of the natives depends almost entirely upon the rice, beans and salt fish shipped from the states.

Compared with the conditions of living within the continental United States, even in the smaller and more remote towns, life in Porto Rico must seem at first to a visitor from the north very difficult, but to be fair one must take into account the vicissitudes through which the country has passed and realize what splendid headway is now being made in the direction of culture. On the other hand, no visitor, even while adjusting himself to the mode of life in Porto Rico, can fail to be charmed by the idyllic beauty of her scenery and the splendor of her setting under the tropic skies.

PHYSIOGRAPHIC HISTORY

The physiographic history of Porto Rico takes us back to an oldland composed of a complex mass of igneous rocks (Fig. 4). The rock types involve sedimentaries of volcanic origin and intrusive masses ranging in size from those showing only a few feet of outcrop to the largest one covering almost one-eighth of the island. Under the influence of subaërial erosion, this oldland was reduced to a rather perfect peneplane except for two well-defined monadnock groups. The smaller of these groups now comprises the Luquillo Mountains at the eastern end of the island. The larger one is known as the Cordillera Central and forms the main crest of the mountainous area of Porto Rico. It is probable that Porto Rico is essentially a block or horst bounded by faults, and it is likely that several of the larger elements comprising the oldland mass are due to faulting which antedated the first peneplanation. No direct evidence on this point is available.

Uplift of this the first peneplane stimulated a new cycle of erosion. Over most of the island only a mature stage of dissection was reached in this new cycle, but along the north coast an east-west belt about ten miles wide was reduced to base-level, which for convenience may be known as the second or lower peneplane. A corresponding belt on the south side of the island was also worn down far less effectively, probably be-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cause of inadequate rainfall. Submergence of much of the oldland mass then permitted the deposition of a coastal plain upon both the north and south sides of Porto Rico. That on the north side covered most of the lower peneplane at the east end of the island and

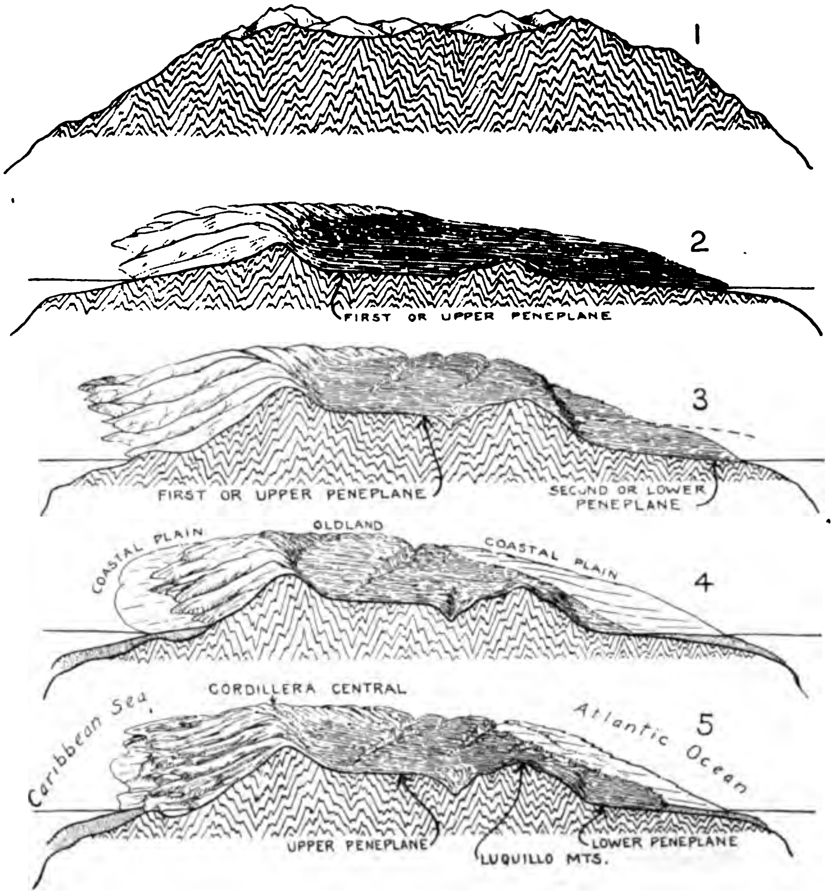


FIG. 4.—*The main stages in the physiographic development of Porto Rico*

1. The initial complex mountain mass of Porto Rico.
2. After the first peneplanation. Showing the monadnock group forming the Luquillo Mountains and the cordillera Central.
3. The peneplane has been uplifted and dissected and a second lower peneplane has been formed along the north side of the island.
4. The whole island has been lowered, its northern and southern flanks have been covered with coastal-plain deposits, and the mass as a whole has again been raised.
5. Dissection of the coastal plain has taken place. Distinct cuestas appear on both the north and south sides of the island.

in the western part even extended so far inland as to rest upon the first or higher peneplane; that on the south side was deposited upon a very irregular oldland surface. Dissection of both the coastal plains was then initiated by uplift. The coastal plain on the north side acquired a well defined belted character, exhibiting two pronounced cuestas, each surmounted by the so-called haystack hills of the limestone country. These parallel east-west belts of hills alternate with other belts of lower country, which on account of the sharpness of dissection have a plateau-like aspect. The inner cuesta of the north coastal plain in places fronts a broad inner lowland from which the basal deposits of the coastal plain have been removed. The outer or northern cuesta usually looks down upon one of the plateau-like belts just mentioned. On the south side of Porto Rico a distinct cuesta was developed, but occasionally it is obscured by the irregular topography of the oldland upon which it rests.

After the dissection of the coastal plains the entire coast suffered a slight submergence, the result possibly of the melting of the continental ice sheets at the end of glacial time. The recent changes which have taken place since this submergence involve the deposition of alluvium along stream courses and its dissection to form terraces, the building of extensive alluvial fans on the south coast, the silting up of bays, and the work of the waves and wind, which has been most pronounced on the north side of the island. Finally there is some evidence of a slight emergence at a very recent date.

For ease of reference the physiographic history of Porto Rico may be divided into several events or stages which can be tabulated as follows:

1. The oldland, a complex mass of igneous rocks consisting of sedimentaries and intrusives subjected to subaërial erosion.
2. The first or higher peneplanation with monadnocks.
3. Uplift, mature dissection, and development of the second or lower peneplane on the north and south sides.
4. Partial submergence and deposition of coastal plains on the north and south coasts, to be known as the Tertiary coastal plains.
5. Uplift, dissection of coastal plains, and continued erosion of the oldland.
6. Slight drowning of entire coastline.
7. Recent changes involving:
    - *a.* The deposition of alluvium in stream valleys, in drowned bays, and as alluvial fans on the south side of the island.
    - *b.* Wave and wind work.
    - *c.* Slight emergence.

The discussion of these stages will follow the order of succession of events as given above, and in pursuing it the reader will do well to make frequent reference to the accompanying large map.

THE OLDLAND

The rocks of the oldland comprise what has been termed the Older Series by Dr. Berkey. While over large areas the erosion of the oldland mass has not been appreciably affected by variations in the character or the structure of the rocks, there are districts where quite the reverse is true. A brief consideration of the rock types and the simpler deformations which have taken place in the older series will therefore be of distinct help in appreciating the present topography.

Volcanic Tuffs and Shales

As is to be expected in a region isolated from a continental mass, practically none of the formations have a clastic derivation. Volcanic tuffs represent the most abundant of the rock types and they are usually massive in habit and made up of andesitic fragments. This implies a practical absence of quartz, a condition which is true also of the shales. These two rock types, together with the igneous intrusives of the andesite-diorite family, make up the bulk of the older series, and as they grade into and are frequently indistinguishable from each other it is practicable to draw a few generalizations regarding the effect of erosion upon them.

Although it is usually true that weathering has gone to considerable depths, 20 to 30 feet being quite common, most streams are cutting into rocky beds. Berkey (1915, p. 34) has remarked upon the striking manner in which badly decayed outcrops resist destruction or removal by ordinary weathering and erosion agents. He mentions three factors to account for this stability of the soil mantle:

> One is the clinging character of some of the vegetation which tends to bind the soil together; another is the small range of temperature variation, which reduces disintegration or disruption tendencies to a minimum; and still another is the low content of inert or refractory materials, such as quartz, in the rocks whose destruction has furnished the soils; all of which factors favor the making of a specially tenacious soil.

It is probable that the last factor is by far the most important.

In general, the hillside slopes throughout the older series are very steep, 30 degrees being exceedingly common and 40 to 45 degrees not rare, but this does not hold true in the granite areas where rolling topography and gentle slopes are the rule. In spite of the fact that the tenacious character of the soil, due to its high clay content, enables the vertical cuts of trails to stand for long periods and prevents the washing of steep hillsides, it is no uncommon thing to see slumping of the ground even on moderate slopes, and occasionally land slides of really great proportions. A large landslide may be seen a few miles north of Yauco on the trail to Maricao, where the mountain sides for the space of a thousand feet above the valley floor have given way.

Another factor which may be of significance in developing steep slopes and the characteristic *cuchillo* or knife-edge divides on the members of the older series is the torrential character of the rainfall. The average annual rainfall over the upland portion of Porto Rico is between 80 and 90 inches, or more than twice that for the vicinity of New York. But, unlike the precipitation of middle latitudes, where the duration is to be measured in hours, and even days, and the amount in hundredths or tenths of an inch, the average duration of a shower in Porto Rico is ten or twelve minutes, and there are numerous instances of successive showers which totaled 10 inches rainfall in twelve hours, while amounts of 4 to 5 inches in twenty-four hours are of frequent occurrence. A record of 23 inches for twenty-three hours, as an example of an extended period of heavy precipitation, and of 1 inch in nine minutes for a short period may suggest to the reader that important consequences must result from the accumulation and run-off of so great a volume of water in so brief a period of time. Those portions of Porto Rico which have only moderate rainfall, but apparently the same general rock make-up as that of the mountainous rainy district, exhibit much smoother and more rounded slopes.

Another phase of the situation, dependent upon the plasticity of the weathering product derived from the quartz-free volcanics, is the imperviousness of the soil mantle. This encourages a large and exceedingly rapid run-off, as may be appreciated from the fact that many streams immediately rise 15 to 20 feet after heavy showers. In one case the Plata River, twenty-five minutes after it began to rise, poured over the dam near Comerio in a sheet 15 feet or more in thickness throughout the entire 575 feet length of the dam, the flood continuing all day at 10 feet above the dam.

The impervious character of the soil causes not only a rapid run-off, but also an accumulation of water in all the little pockets and irregularities of the surface. In consequence the trails over the upland portion of the island, except during the comparatively dry months of January and February, are often veritable sloughs of red mud, which is both unctuous and tenacious and exasperatingly slippery.

GRANITE

Next in size to the areas of tuffs, shales, and associated igneous intrusives making up the bulk of the island are two or three areas underlain by large intrusions of granite. The largest of these covers most of the southeast corner of the island from Caguas to Yabucoa. In general, the granite is less resistant than the volcanic rocks and most of this region has been reduced to a more or less open lowland. At the north the limits of the lowland coincide rather closely with the extent of the granite, but the southern margin is less definite and much of the granite still retains the upland level. Throughout the granite area the hillsides are covered with large weathered blocks and boulders, and the soil is distinctly granular and resembles a fine gravel. There is a marked contrast between the cleaner condition of the native huts and the tidier way of living in this area, where the soil is porous, and the usual filthy condition which prevails over most of the island where mud is such an important factor. A second granite mass, of unknown extent, is found in the region about Utuado, in the west central part of the island, but its effect upon the topography is not marked. The granite is massive and jointed, and in a minor way some control is exerted upon stream position. Even a master stream like the Arecibo River follows joint planes for short distances. Pot-holes, a feature observed practically nowhere else in Porto Rico, occur along this river, and their presence is ascribed to the substantial and massive character of the granite.

SERPENTINE

Besides the granite intrusions there are in the western part of the island one or two masses of serpentine of smaller areal extent. They resist erosion more readily than the adjacent rocks and appear as round, full-bodied forms topped by more or less level surfaces. They constitute the so-called *mesas* near Mayaguez and similar larger masses farther east. The weathering of the serpentine has produced a thick, red covering of limonitic soil and has given rise to the smooth-flowing outline of the crest of the mountains which is distinctly characteristic of the region north of San German, where the bulk of the range looks much like the back of a gigantic elephant.

LIMESTONE

The fourth group of rocks occurring in the older series exerts by far the most effective control over the erosional forms. These are the crystalline limestones. Almost invariably they stand up as distinct ridges, despite their high solubility and the frequent caverns to which this character gives rise. The two most prominent of the limestone belts make up the chain of hills known as the *Cerros,* running from Cabo Rojo to Yauco, and a parallel chain to the south extending from Boqueron Bay to Guanica. The relation between these two belts is discussed below under "Structure." Another limestone ridge runs from Juana Diaz eastward to Salinas, the formation being known as the Coama tuff limestone. Other smaller belts occur in the interior, as, for instance, the Aguas Buenas limestone; but they are usually too insignificant in thickness materially to affect the topography, although their ragged white outcrops may be a conspicuous feature of the landscape.

STRUCTURE

The usual trend of the members of the older series is in a west to east or a northwest-southeast direction (Fig. 3). Over large areas it is next to impossible to determine the strike at all, owing to the massiveness of the formations and their decomposed condition; and even where the strike is to be recognized the yielding character of the rock, due to the advanced state of decay, makes it a negligible factor in controlling stream position.

South of San Juan a definite alignment of features in a northwest-southeast direction reflects a greater degree of structural control than is commonly the case in the volcanic members of the older series. There is a high, continuous ridge which persists from near La Muda southeastward to the gap cut by the Rio Grande; and running parallel to the ridge on its south side is a distinct subsequent lowland developed on weaker rock, not occupied throughout its length by any one stream. The road from San Juan to Caguas follows this narrow lowland for several miles east from La Muda. At the west end of the island the east-west trend of the Atalaya Range is in sympathy with the strike of the formations, as may readily be seen at many places on its southern flank.

In the region about Coamo Springs there is a well-defined parallelism in the series of ridges developed upon the Coamo limestone and its associated formations. This limestone, which has already been mentioned, strikes from the northwest to the southeast, has a pronounced dip to the southwest, and gives rise to the most marked feature in this stretch of the southern coast. The main ridge or hogback in its highest part, in the vicinity of Juana Diaz, has an elevation of almost a thousand feet higher than most of the hills of the coast region. Its uneven crest, interrupted by several deep water-gaps, descends more or less regularly until it pitches beneath the alluvial plains near Salinas, but large outliers are found along the continuation of its strike at Central Aguirre.

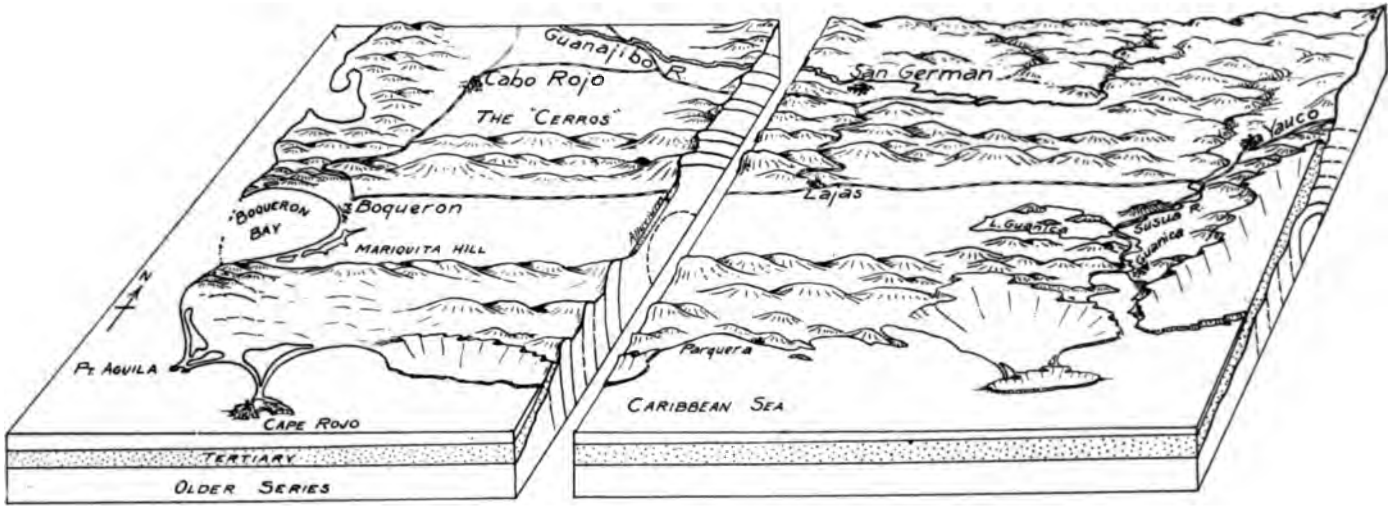


FIG. 5.—*Block diagram of the southwest corner of Porto Rico*

The structure of the older series is a huge anticline pitching west at Boqueron and east between Yauco and Guanica.

The southwestern corner of Porto Rico (Fig. 5) appears to be a huge anticline, pitching to the west below Boqueron Bay and to the east beneath the Tertiary series at Yauco. The north and south limbs of the anticline stand up as two parallel ranges separated by a broad valley developed on the axis of the anticline. The north limb of the anticline is known as the *Cerros* and is by no means a well-defined ridge. Rarely can the northward dip of the limestone and adjacent formations be noted. The topography developed upon the southern limb is expressed by a series of more or less parallel and elongated hills which are thoroughly suggestive of Appalachian ridges on a reduced scale (Fig. 6). On the north side of Boqueron Bay, and in particular near Guaniquilla Point, the usual east-west strike of the formations swings around toward the south, and it is one of the resistant layers which forms the barrier across the mouth of the drowned anticlinal valley represented by Boqueron Bay.

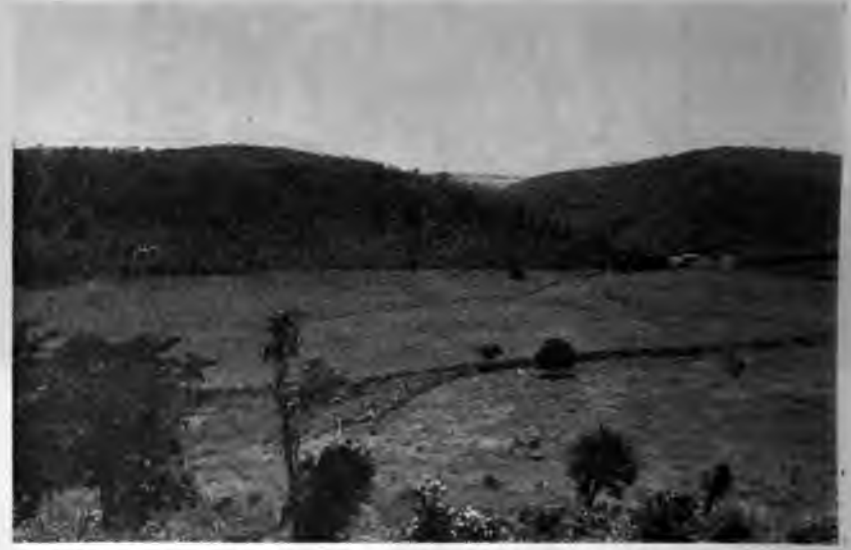


FIG. 6.—*Appalachian ridge structure in the oldland rocks between Boqueron and Parguera*

A subsequent valley, in the foreground, and a ridge transected by a water gap.

THE FIRST OR HIGHER PENEPLANE

THE PENEPLANE

As one approaches San Juan by boat from the north the remarkably even skyline over the central part of the island presents striking testimony of the first recorded period of base-leveling imposed upon the folded mass of the older series. If there were an earlier planation, all evidence of it was removed by the wide extent and perfection of the erosion which produced the peneplane represented by the present summit levels. The notches of the Plata and Bayamon rivers are the only breaks in the otherwise continuous skyline and give the first intimation of the thorough dissection which has occurred. Deep gorges, bold canyons, in fact (Fig. 7), are the rule, and the ramifications of the headwaters in steep-sided valleys and ravines is unusually bewildering to one exploring the mountains on

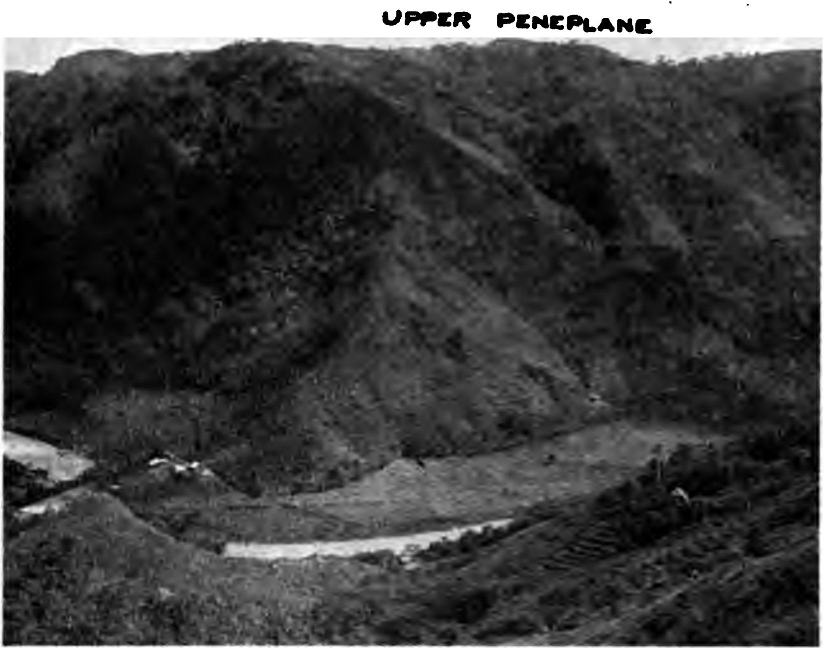


FIG. 7.—*Valley of the Manati River above Ciales*

A gorge in the oldland cut below the level of the upper peneplane.

foot. The peneplane was best developed, or at least its remnants have been best preserved, in the central part of the island. All the way from the Plata River region westward to Lares its fairly accordant skyline forms the controlling element in the topography. West of Lares the peneplane has been so extensively dissected that only isolated remnants and spurs are to be recognized, the Atalaya Range forming the largest unit; and east of Caguas the prevailing level of the country is so much below the upland surface that it must be considered as a lower base-level formed at the time of the second peneplane. The same is true of the region about Cayey (Lobeck, 1919, p. 535).

It is believed that the accordant level of the hill-tops on Vieques, having an elevation of about 600 feet, represents the upper peneplane, this assumption being based mainly on the fact that the Tertiary formations rest upon a lowland cut below that level. On Culebra there is no accordance of level, neither is the Tertiary represented to furnish a key to the situation, but because of similar orders of magnitude of the features to those of Vieques it is probably safe to assume that the tops of the hills roughly indicate the upper level (Fig. 40).

MONADNOCKS

THE LUQUILLO MOUNTAINS

This range stands up as a prominent mass at the eastern end of Porto Rico. The upper peneplane flanks it only on its western side; above it the mountain summits rise over a thousand feet; elsewhere they drop in long radiating spurs to the coast or abruptly to the adjacent lowlands. Having an elevation of nearly 4000 feet, these mountains form one of the most imposing features of Porto Rico.

The best explanation for the position of this monadnock mass is the presence of more resistant rock types, though in the field the rocks here appear to suffer weathering as readily as those over most of the adjacent upland. A puzzling feature is the fact that all sorts of rocks are represented in the area, including tuffs, limestones, and even granite, which is so non-resistant in the tropics, on the southern flank of the range. The possibility that the mass represents an upwarped part of the upper peneplane can not readily be entertained because the peneplane remnants appear to fringe it so nicely on the west and to form a narrow shelf on the south, and because the peneplane can not be recognized elsewhere about its base. It is quite possible that a better knowledge of the rocks involved would show that the higher areas are actually made up of more resistant types.

The Luquillo Mountains, as a whole, are maturely and deeply dissected, and though at a distance they appear as a unit mass, a traverse of the range shows them to be made up of several culminating peaks separated by gorge-like valleys 1000 to 2000 feet deep. El Yunque, "the anvil," is the highest of the peaks and has an altitude of close to 4000 feet. Although the Luquillo Mountains are forested, rock ledges and bold and imposing cliffs are not uncommon. The Luquillo National Forest covers most of the range and is the only extensive part of Porto Rico still preserving the virgin timber. Contrary to a general conception, this original tropical forest is not an impassable jungle, but is pleasingly open and park-like. Tree ferns abound, and occasionally one meets with flowers of great brilliancy, but there is almost no animal life. Even birds are rare. The sound of running water is always to be heard, so frequent are the streams. The higher parts of the range are almost continually drenched in a heavy mist. Nowhere else in Porto Rico may one walk for hours without seeing one of the thatched huts of the natives or without meeting people at every step.

THE CORDILLERA CENTRAL

Practically all of the other residuals rising above the peneplane level are concentrated in a chain of peaks along its southern margin, known in the western part as the Cordillera Central and further to the east as the Sierra de Cayey. Many of these peaks, especially in the west, rise to the same or to an elevation even greater than those of the Luquillo Mountains. Viewed from the south, the whole range has the appearance of a ragged escarpment with long, irregular spurs trailing down between steep-walled and cirque-like valley heads. Just as the lower peneplane, to be described later, reached a far greater degree of perfection on the north coast than on the south, due presumably to the abundance of rain on the north side and its almost complete lack on the other, so it seems that the same cause may have been effective in the disposition of this chain of monadnocks along the southern edge of the higher peneplane. In the region south of Adjuntas a wide belt of country is involved in the Monadnock group, and here it is not always easy to say just what the elevation of the peneplane is; but further east the belt becomes narrower, and in the Sierra de Cayey only one or two masses rise above the well-marked peneplane level.

THE SECOND OR LOWER PENEPLANE

From San Juan on a clear day the sharp break between the higher and lower peneplanes twelve miles to the southwest is a sufficiently marked feature to be easily noted. The escarpment was mentioned by Semmes in his report on the San Juan District. In the space of only a mile or two there is a descent of 1000 feet or more northward to the lower peneplane. Although Semmes briefly entertains the idea that there has been simply a warping of one peneplane, all the evidence, both here and elsewhere, points to the later development of a lower base-level. The strongest evidence is the fact that the lower level is to be recognized between the spurs coming down from the higher one, and that more or less extensive basins like the Caguas and the Cayey Valleys have been opened out upon softer rocks below the prevailing upland. A corresponding lower level on the southern side of the island has also been produced by erosion, but the stage of development is not so advanced as that which characterizes the lower peneplane on the north coast.

The escarpment, which virtually marks the northern limit of what is known as the mountainous part of Porto Rico, is not to be seen west of Ciales. The coastal plain in the western half of the island laps so far over the oldland as to bury completely the lower peneplane if it was developed there. Just south of Corozal the break between the two peneplanes is more marked and regular than anywhere else. Further to the east the spurs from the upland level become more and more confusing until directly south of San Juan, in the region around La Muda, it is quite impossible to distinguish with any degree of satisfaction between the elements of the landscape.

It is not possible to know just how far the Tertiary coastal plain formerly extended over the lower peneplane on the north coast, but it is quite probable that much of the area was covered and that the inner lowland now developed represents a stripped belt. Were it not for the irregular surface, both on the north and south sides of the island, upon which the Tertiary was laid down, it might be argued that wave planation was a factor in developing the lower peneplane. But the ruggedness of the buried surface, especially on the southern coast, favors the theory of subaërial erosion, although it is not unlikely that waves were effective during the transgression of the sea in which the coastal plain was deposited. Throughout the eastern half of the north coast region, from Morovis to the base of the Luquillo Mountains, the lower peneplane is a gently rolling surface with few interruptions rising above the general level. The streams are numerous, but the depth of dissection is rarely over 100 to 200 feet (Fig. 8).

On the south coast conditions are quite analogous to those on the north side of the island, but the reduction toward a lower level did not advance far enough to justify the term peneplane over any extended area. As previously suggested, this condition is explained by the contrast in precipitation on the north and south coasts. On the north coast the stage of development reached was one of old age, since rejuvenated, whereas on the south side of the island the region in general may be described as still in maturity.

Although the general elevation of the region a few miles back from the south coast is much below that of the upland peneplane level, there is still very great relief, and the whole belt of country flanking the southern margin of the upland is characteristically rugged. The escarpment marking the break between the higher and lower levels on the south side of Porto Rico is the most extensive physiographic feature on the island and at the same time the most imposing. It would be even more imposing if it were not that the spurs and foothill country cover such a wide belt and have such considerable elevations as partly to detract from the prominence of the main crest. In the eastern portion near Guayama the face of the escarpment is exceedingly irregular and is broken by great cirque-like valley heads, whose walls attain a steepness not exceeded elsewhere in Porto Rico. Slopes of 40 degrees are common, and even 50 degrees is frequently noted. In its western half the upland margin has a fairly definite east-west trend and the foothill country becomes narrower.

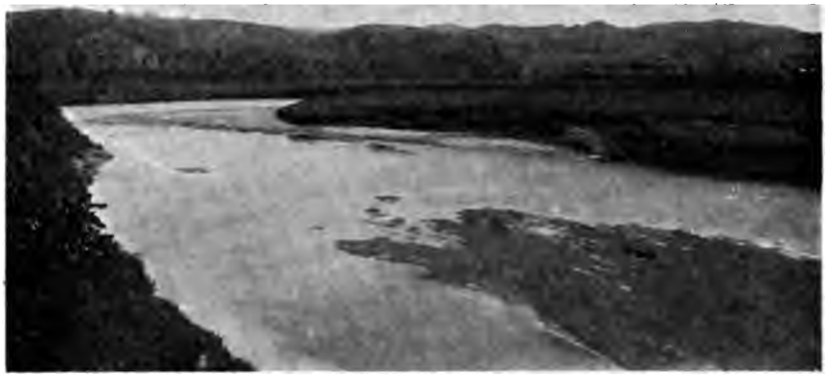


FIG. 8.—*The valley and flood plain of the Rio Grande de Loiza near Carolina*

The tops of the hills represent the surface of the lower peneplane below which the valley has been opened out.

We may say, then, that it is this foothill country on the south side of Porto Rico which corresponds with the lower peneplane on the north side. On the north side rejuvenation is evidenced by the incision of the streams 200 feet or so below the peneplane level; on the south side the effect of the uplift is not so apparent, because the new cycle was introduced while the work of the earlier cycle was still in its youthful stage, and the result was a continuous down-cutting. Locally, however, there is some suggestion of the development of a lowland before the advent of the new cycle.

A study of a typical profile across the island and a comparison of the lower peneplane on the north and south coasts both above and below sea-level is helpful to an appreciation of its true character. Such a profile is shown in Fig. 9, which represents an approximately north-south section through San Juan. The essential features to be noted are:

a. The higher peneplane forming the great upland portion of Porto Rico, fringed along its southern margin by the chain of monadnocks known as the Cordillera Central.

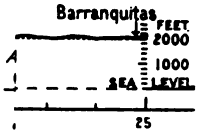
b. The lower peneplane, well developed on the north side of the island, but represented on the south side by a belt of greater ruggedness.

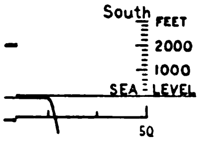
c. The pronounced break or escarpment dropping down from the upper to the lower peneplane on both the north and south sides of Porto Rico.

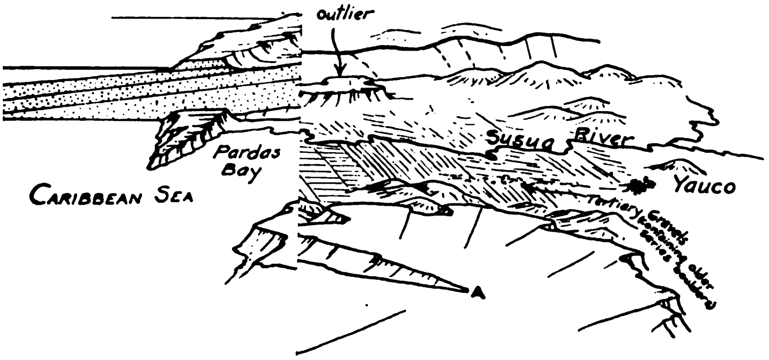
d. The extension of the lower peneplane as a continental shelf beneath the Atlantic Ocean on the north side of the island and beneath the Caribbean Sea on the south side.

e. Remnants of the Tertiary coastal plain resting upon the lower peneplane of the north coast in the region of Bayamon. On the south coast alluvial deposits bury some of the irregularities of the lower peneplane. Further west along this same coast similar irregularities are buried under the cover of the Tertiary coastal plain.

The progress of erosion during the second cycle is attested not only by the denudation of the north and south coastal areas, but also by basins in the interior of the island, notably two in the eastern part. The larger of these, which for convenience may be known as the Caguas Valley, is drained in its western part by the headwaters of the Rio Grande and in the east by several small streams flowing in the opposite direction. Its reduction to a lower level seems to be due entirely to the weakness of the underlying granite rock. The high remnant of the upper peneplane which forms an imposing barrier on the north side of the entire Caguas lowland has been trenched by a narrow valley which serves as an outlet for the Rio Grande. The southern margin of the lowland is more difficult to define because in many places the higher peneplane is not so well preserved. In general, the smooth and gently rolling surface of the low-







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land has strong resemblance to the lower peneplane of the north coast, but the abundance of weathered granite blocks which cover it give it quite a different aspect in detail. In the northwestern part of the Caguas lowland between Caguas and Gurabo the rolling country representing the lower base-level has been opened out by the Rio Grande and its tributaries, whose flood plains lie 200 to 300 feet below the surface of the lowland. Some hills of more than ordinary prominence have their bases buried in the alluvium. They trend in a general east-west direction in accordance with what seems to be the structure of the older rocks. The average elevation of the surface of the Caguas lowland is about 550 feet, which is over 1000 feet below the bordering upland. Whether the rather high and more or less open valley in which the town of Aguas Buenas stands is a correlative of this same lowland it is difficult to say, but it seems probable and indeed almost certain that all the basin-like depressions and occasional broad valleys, which break up the upland surface and which are quite common in the eastern half of Porto Rico, were formed during the same cycle of erosion marked by the development of the lower peneplane on the north coast. In the region around Cidra the high upland level has not been preserved, neither has a well-defined lower base-level been opened out, except possibly very locally.

The second depression, known as the Cayey Valley, is much smaller and stands at a far greater elevation than the Caguas lowland, but nowhere shows a well-defined lower peneplane. It is drained by the headwaters of the Plata River, which doubtless have discovered more yielding formations in this part of their course than a few miles downstream, where the valley is narrow and gorge-like.

Erosion at the western end of the island during and since the second period of base-leveling seems to have proceeded continuously. The result has been simply the mature dissection of the higher upland. The demarcation between the different cycles is not expressed by any well-marked lower peneplane such as has been described for the north coast. That some of the valleys are really the time equivalents of the lower peneplane is suggested by the fact that they are filled with deposits of the Tertiary coastal plain where it now laps over the spurs of the higher upland, thus showing that the valleys hold the same position relative to the upland as the more extensive lower peneplane does further to the east. In the case of such a stream as the Culebrinas River, it is not possible to demonstrate exactly how much of the valley was cut before the deposition of the Tertiary coastal plain or how much afterward, for the reason that it is difficult to determine just how much of it was filled with the Tertiary deposits. The river instead of being a subsequent stream developed at the base of the Tertiary cuesta, as it appears to be, is in reality a stream which has resumed a former course as the limestone which buried its original valley was worn and dissolved away. Further mention of this will be made under the discussion of post-Tertiary erosion.

The distinction between the two periods of base-leveling can hardly be made in the southwest corner of the island, but it is highly probable that erosion during the second cycle opened out two broad valleys, that of the Guanajibo River and the Boqueron-Yauco anticlinal valley, almost to their present extent before the Tertiary period. A point in favor of this interpretation is the fact that the Tertiary in the Yauco-Guanica region filled the end of the broad Boqueron-Yauco anticlinal valley. One large hill of coastal plain deposits and many remnants in the form of basal gravels still remain.

On Vieques the work of erosion during the second period of base-leveling produced the lowland and the valleys on the east and south coasts, now partly covered with the Tertiary coastal plain deposits. On Culebra the development of the large valleys probably proceeded during this time. These valleys, like the ones on Vieques, have since been drowned. The largest, known as Great Harbor, was formerly a coaling station for the United States Navy.

In brief, the second period of base-leveling is represented on the north coast of Porto Rico, east of Morovis, by a well-developed peneplane. On the south side of the island the same time interval is represented in general by the development of a belt of rugged country; in the interior by the erosion of the Caguas and Cayey valleys; on the west end of the island by the mature dissection of the higher upland, and by two broad valleys in the southwest corner; on Vieques by the formation of broad valleys, since drowned, and of the lowland on the south coast; and on Culebra by the excavation of valleys, later drowned like those of Vieques.

DEPOSITION OF THE TERTIARY COASTAL PLAIN

The character of the oldland surface upon which the coastal plain was laid down and the nature of the material deposited strongly merit careful consideration if a clear explanation is to be had of the features later to result from the dissection of the coastal plain. It is especially important in this case because Berkey (1915) believes there is a fault between the Tertiary coastal plain and the oldland on the south coast, whereas the present writer has come to the conclusion that all the evidence cited in favor of a fault can better be accounted for on the basis of an alternative interpretation. Three essential facts may be presented in this connection. First, the Tertiary coastal plain on both the north and south sides of Porto Rico as well as on Vieques was deposited in many places upon a diversified oldland surface, and this fact, it is believed, explains the apparent faulting in several localities. Second, the basal beds of the coastal plain, where deposited upon an irregular oldland, frequently contain many boulders and gravel beds of the older rocks. Recognition of the origin of these gravels makes possible a better understanding of the former extent of the coastal plain. Third, in a few localities where the Tertiary coastal plain rests upon a comparatively smooth oldland the basal beds are represented by a red clay which appears to have been derived from the oldland. The significance of these facts may now be considered.

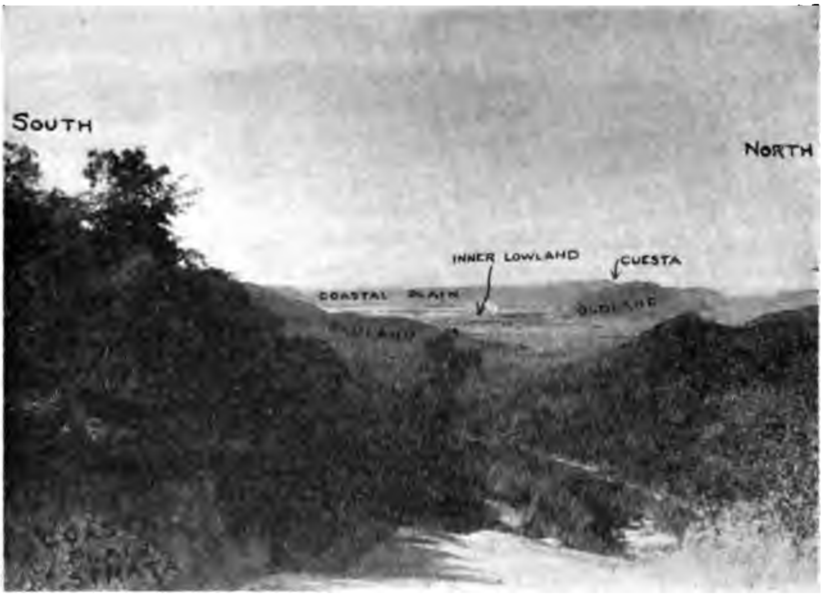

FIG. 11.—*The inner lowland at Guanica*

Showing the inface of the Tertiary coastal-plain cuesta, where it is being stripped from the hills of the irregular oldland surface. See Fig. 10.

No part of Porto Rico shows more clearly the relation between the coastal plain and the oldland than the region about Guanica on the south coast. The general relation between the Tertiary and the older series in the Yauco-Guanica region may be understood by referring to a diagram (Fig. 10) and photographs (Figs. 11 and 12). Examination of this diagram will show that the Tertiary has been deposited upon a very hilly oldland, representing the dissected eastward pitching end of the Boqueron-Yauco anticline. Immediately south of Yauco the hills are of crystalline limestone of the older series and these are overlapped on the southeast by the Tertiary cuesta. Although they are more or less interrupted by gaps, permitting direct access from the flood plain of the Susua River eastward to the Tertiary, these oldland hills can be traced in a swinging arc as far south as Guanica. Here, just east of the town, some bedded volcanics are associated with the limestone. They strike northeast-southwest or east-west and are presumably a continuation of the formations having an east-west trend at Guanica Central. The presence of a large hill of Tertiary as well as abundant occurrences of the basal gravels proves that this valley had reached approximately its present development before Tertiary time. This belief, that modern erosion changes are not to any considerable degree accountable for the present size and shape of the older series hills, but that they are simply being unburied of their Tertiary cover, is abundantly strengthened by a study of the district adjacent to Guanica Central. At Guanica Central the oldland hills can be seen actually emerging from beneath the coastal plain, and on their flanks there still remains a coating of chalk, attesting the recency of their unburial. This deposit may be seen at the base of the crystalline limestone hill near the stone-crushing plant of the Guanica mill. Nearer to the Guanica Central the coating left upon some of the dark older series volcanic rocks appears

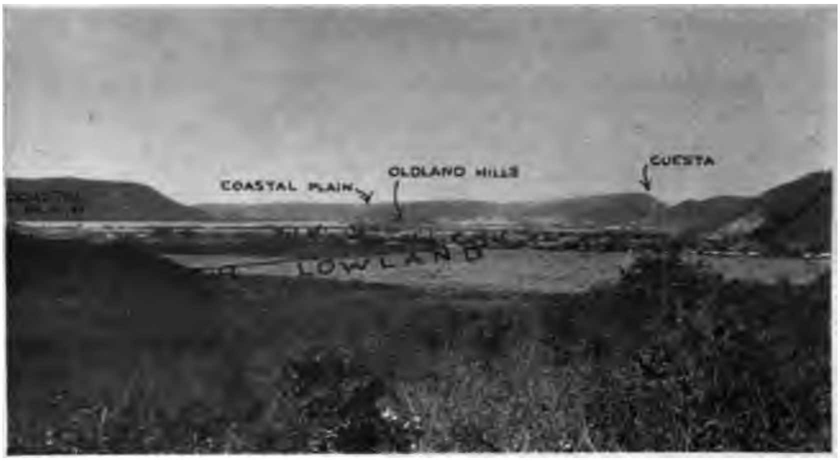

FIG. 12.—*The inner lowland at Guanica*

Showing the inface of the Tertiary coastal-plain cuesta where it is being stripped from the hills of the irregular oldland surface. See Fig. 10.

like a sheet of plaster or whitewash only a fraction of an inch in thickness. There are numerous other localities where the irregular character of the oldland surface may be readily observed. For instance, just back of Ponce to the northwest there is a group of hills representing an isolated part of the Tertiary cuesta. It is separated from the oldland by a narrow inner lowland not more than half a mile or a mile wide. On the north side of the miniature inner lowland the irregular hills of the oldland are as high or even higher than the cuesta face. The beds of the Tertiary coastal plain are in no way disturbed along the cuesta front. They are primarily chalky in character, with few fossils, and belong to what Berkey has termed the "Ponce chalk beds." The flanks of the oldland hills facing the lowland are covered over with loose coral heads and soil, but on the summit the older series rocks are abundantly exposed. The inference drawn from these facts is that the Tertiary was laid down upon an irregular oldland surface and that the hills nearest the cuesta, having been most recently stripped of their Tertiary cover, represent approximately the oldland surface at the time of deposition. If this is true, there is good reason to expect to find in places an abrupt transition from the Tertiary beds to the older series, thus simulating in the field conditions which commonly accompany a fault. Not far from Ponce, on the road to Adjuntas (K 4.8), a natural section is provided by the Canas River, and there one may see a sudden passage from the horizontal chalky beds of the coastal plain at the south to the dark oldland rocks at the north. The actual contact is more or less confused, but on either side within short, horizontal distances the older and the younger series are well displayed and there is no disturbance in the bedding of the latter. This is one of the localities which Berkey cites as evidence for a fault, but the writer is convinced that the abrupt transition is due to the irregular character of the oldland surface. Mention may be made of still another place on the south coast. Along the road between Ponce and Peñuelas (K 10), just before it comes out on the face of the cuesta, conditions indicating a sudden change from the coastal plain to the oldland are repeated and additional facts of interest are observed. Berkey bases his reasons for placing a fault at this point upon the abrupt contact, the inclination of the Tertiary strata, and the drag of the beds. These latter features, the writer believes, have been brought about by the collapse of underground caverns and the development of sink-holes, which are of great abundance in this locality and are especially liable to form along the contact of the Tertiary and the older series. The character of the Tertiary here, limestone beds alternating with fine older series gravels, is in keeping with the belief that the Tertiary was laid down very close to the older rocks and militates somewhat against the assumption that faulting of any considerable throw has occurred.

On the north side of Porto Rico the irregularity of the oldland surface is of two kinds. In the eastern part, where the coastal plain rests upon the well-developed lower peneplane, an occasional monadnock occurs. Against these monadnocks the coastal plain deposits now abut abruptly or have only recently been stripped away. Four miles southwest of Toa Alta (K 4, Toa Alta-Corozal road) the cuesta stands directly over a monadnock of the oldland, whose surface still preserves remnants of the Tertiary limestone isolated from the main mass. The second type of irregularity is that found further west, as in the Lares region, where the coastal plain extends so far inland as to bury completely the lower peneplane and to cover partly, or even entirely, the spurs coming down from the higher peneplane. Where the coastal plain reaches so far as to rest upon the surface of the higher peneplane the thickness of the deposits is slight. Where it fills the old valleys between the oldland spurs the thickness of the deposits is great. The present streams are apparently re-excavating the old valleys by a process of subterranean erosion beneath the limestone.

On the island of Vieques the coastal plain rests upon an oldland of decided relief. At the eastern end the Tertiary is represented as a low cuesta which, if continued westward across the small inner lowland, would abut abruptly against the older series hills, while on the south coast the remnants of the Tertiary now form islands in bays of the oldland, as is the case at Chiba Bay.

The fact that the basal Tertiary contains boulder and gravel beds of the oldland rocks is worthy of attention, because it is the basal remnants which frequently provide a clue to the former extent of the coastal plain, and unless their character is recognized they may be mistaken at first for more recent flood-plain gravels. Two miles south of Yauco, in the valley of the Rio Yauco (near the American Railroad bridge), the basal Tertiary is exposed along the carreterre. There is evidence that gravels of material from the oldland rocks are prominent as an element in what are undeniably basal beds of the Tertiary coastal plain. In the road cut are shown the long worm-tubes, so common in the Tertiary, on both the north and south sides of Porto Rico as well as on Vieques. These occur in position, are sometimes 18 to 20 inches in length, and always taper upward. The fact that they are vertical, in spite of the pronounced southward dip of the beds, argues that there was little or no tilting of the strata during uplift, and that the beds were deposited in an inclined position upon the sloping surface of the oldland. On many of the rolling hillsides and in the road cuts around Yauco there are exposed very coarse gravels, which have a superficial aspect much like those of the present alluvial flood plains. These are unquestionably basal Tertiary, and suggest that the conditions on the south coast at and just before the beginning of Tertiary deposition were similar to those of the present. The best and most accessible occurrences are along the main road just east of Yauco and for several kilometers on the road to Guanica. The gravels in several places seem to fill pockets in the same manner as does the alluvium of the modern streams. The presence of the basal Tertiary throughout the valley of the Susua River (Fig. 17) indicates that the oldland hills south of Yauco were at one time completely buried by the coastal plain.

Just east of Juana Diaz the basal Tertiary contains beds of oldland conglomerates alternating with fossiliferous layers. This is a country locally of rolling hills of the older rocks, and while exact contacts were not observed one would infer, with considerable assurance, that the basal Tertiary occurs as patches upon and in the depressions of this older surface. On account of the obscure effects which these basal Tertiary deposits exert upon the topography, the observer is very liable to underestimate their extent, and in mapping the region is apt to consider most of it older series. For several miles along the road west of Juana Diaz the basal Tertiary gravels occur. Casual observation would place them with the coarse gravels of the present flood-plain deposits, though they are sufficiently different in character to be more or less readily distinguished. The beds in which they occur are usually white or gray chalk and the boulders themselves are much more weathered than those of the present streams. On the north side of the island, about a mile east of Moca, on the Lares road (K 7 to K 10), many exposures of a heavy conglomerate of the older rocks are to be seen. These are remnants of the basal Tertiary which filled valleys of the oldland. They are extremely well weathered and in places (as at K 12.1) have the appearance of a soil derived from the decay of the older rocks. Close inspection, however, reveals the fact that the apparent residual soil is in reality made up of bedded conglomerates, with boulders varying in size up to two or three inches in diameter. At the base of the Tertiary cliffs (Fig. 13), on the eastern end of Vieques, there is a thick bed of oldland conglomerate.

In all of the places which have just been described the Tertiary coastal plain rests upon an irregular oldland and its basal beds are made up of conglomerates derived from the older rocks. In contrast with this there are places where the coastal plain has been deposited upon a very smooth oldland surface, and in such places the basal beds are reddish clays with no boulders. Topographically the effect in those places has been the velopment of more or less extensive flat areas where the more soluble o lying limestones have been removed. Such features are to be seen tween Bayamon and Rio Piedras on the north coast. In no other par Porto Rico has the Tertiary been deposited upon such an even surf Most of the inner lowland is a stripped part of the lower peneplane has a distinct seaward slope and monadnocks upon it are rare. The b clayey layers of the Tertiary coastal plain upon which the flat tracts developed cover a part of the inner lowland adjacent to isolated remn of the Tertiary cuesta.

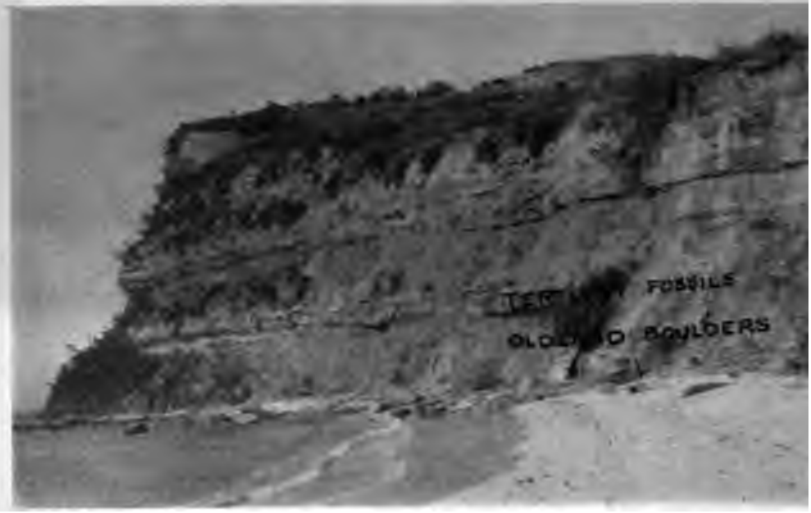

FIG. 13.—*Basal Tertiary south of Yauco, along the Guanica road*

The Tertiary here consists of older series gravels filling former stream channels. one place the actual contact of these beds with the surface of the older rocks ma seen.

It is probable that the coastal plain deposits never arched entirely o the oldland. The occurrence of beds of small gravels, derived dire from the older series at intervals throughout the coastal plain depo and the abundant clay content of the coastal plain limestones, make seem likely that a large area of the oldland remained continuously sub to erosion. The belief that the coastal plain did not reach over the wh island is also substantiated by the abrupt termination of the coastal pl deposits against the lower slopes of the upland mass, especially on south side of the island.

UPLIFT AND DISSECTION OF THE TERTIARY COASTAL PLAIN

CHARACTER OF THE UPLIFT

The uplift of the oldland which brought the Tertiary coastal plain above sealevel appears to have been greatest in the western part of the island in the region approximately between Lares and Yauco. This is indicated by the fact that near these two places, on the north and south side of the island respectively, the north coastal plain and the south coastal plain attain their highest elevations and at the same time reach farthest inland. On the north coast stratigraphic studies by Hubbard, as well as those by Semmes, show that the lowest coastal plain beds in the Lares district (the Lares limestone, lower Oligocene) stand at an elevation several hundred feet higher than the lowest beds further east in the vicinity of Corozal, although the latter are of a higher geological horizon (upper Oligocene). This indicates not only a greater uplift of the island in the Lares region than further east, but also suggests that the Lares area stood at a lower elevation at the beginning of Tertiary deposition. In other words, it appears that the Lares region was uplifted some 500 feet or so higher than the region around Corozal, some 35 miles eastward. A warping of this amount would give to originally level strata a slope of much less than a degree. The warping of the coastal plain, then, while having hardly any effect upon the attitude of the coastal plain beds, has lifted above sealevel a much greater extent of the coastal plain in the western part of the island and a progressively smaller area toward the east. The dip of the coastal plain beds is one or two degrees toward the north away from the oldland on the north side of the island. An inclination of this amount may readily have been the original inclination of the beds at the time of deposition. In fact, on the south side of the island beds having a dip of five to ten degrees apparently preserve their original angle, for they are traversed diagonally by worm-tubes, still standing in the vertical position of growth. Therefore it is unsafe to cite this northward dip as due to the greater elevation of the oldland. It would appear more reasonable to say that the oldland and the coastal plain portions of the island were uplifted uniformly above the sea, but that the western part of the island suffered a greater elevation than the eastern.

While a differential uplift appears to offer the best explanation, it nevertheless may well be argued that the coastal plain was not warped during uplift but that its various dips are the initial dips of deposition due to the fact that the plane upon which it was laid down was not a horizontal one. In other parts of the world marked dips have been taken to indicate warping but there is a tendency among geologists to give credit to the belief that in such places the strata were laid down on sloping surfaces which were uplifted with little or no warping. The dome-like form of Wisconsin, for example, may be due to the fact that the sediments were deposited upon a buried dome which was later uplifted uniformly. The fact that a younger formation stands at a lower level than an older one a few miles distant does not necessarily mean that warping has taken place.

ASSUMED FAULTING

A problem of especial interest in connection with the uplift of the coastal plain is the question of faulting between the oldland and the coastal plain on the south side of the island. Berkey has studied this locality, and finds evidence which justified him in placing an east-west fault running approximately from Juana Diaz to Peñuelas (see map in his report). This matter, therefore, engaged a good share of the writer's attention, with the result that he came to a radically different conclusion, as has already been mentioned. An explanation of some of the evidence offered by Berkey is entered into more fully in other sections of this report, where it appropriately finds a place; but for the convenience of the reader, the whole argument is here brought together in brief form. First of all, Berkey cites the abrupt manner in which the coastal plain deposit of the south coast suddenly terminates against the oldland mass. He notes this relationship a few miles north of Ponce on the Ponce-Adjuntas road (K 4.8), and near Peñuelas (K 10) on the Ponce-Peñuelas road, as well as in the valley of the Jacaguas River, just north of the military road at Juana Diaz. Since abrupt changes of this kind are the rule wherever a coastal plain has been deposited upon an irregular surface, evidence of this character can not safely be cited as a proof of faulting, and it has been shown that this is distinctly the case on the south coast of Porto Rico. A careful study was made of the above-mentioned localities, as well as of many others, and the conclusion was that in each case the abrupt passage from the coastal plain formations to the rocks of the oldland is due to the irregular surface of the oldland upon which the coastal plain strata were laid down. In the second place, Berkey refers to the "total failure on the south side of the island of the topography characterizing the change of formation as noted on the north side of the island." [1] He presumably refers to the well-defined cuesta and inner lowland of the north coast. It is true that on the south side of the island the cuesta is not so continuous a feature, but by no means is it entirely lacking, and if it appears vague in places this is always due to the irregular oldland upon which it rests. Finally, Berkey notes the existence of "crush zones, slight folding and drag" in the strata of the coastal plain deposits near Peñuelas (K 10) on the Ponce-Peñuelas road, and the pronounced tilting of the coastal plain beds a mile southwest of Juana Diaz. All of these disturbances are extremely local and, in the writer's opinion, are due unquestionably to the collapse of the beds about sink-holes. These are very common features and exert a marked effect upon the topography in both localities cited. A more thorough discussion of this point is taken up in a subsequent part of this report.

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[1] Personal communication.

Dissection of the Coastal Plains

The dissection of the coastal plains has resulted in a main cuesta and a series of more or less distinct secondary cuestas, with other features of a belted coastal plain, on both the north and south coasts; but the drainage development departs from the normal owing to the overwhelming preponderance of limestone in the coastal deposits. An essential point to be kept in mind is the irregularity of the oldland surface upon which the limestone was laid down. This affects not only the relative height of the cuesta in different places along its front, but it also exerts a control upon the position of underground river systems. By the collapse of overlying beds the subterranean channels eventually form the main drainage lines of the district. As the north and south coastal plains are isolated units, it is believed that a clearer presentation of the main features can be made by treating each separately.

THE NORTHERN COASTAL PLAIN

Normally a coastal plain when first uplifted above the sea is drained by consequent streams of two types—initial and extended. Since it is thought, for several reasons, that the coastal plain never spread much further upon the oldland than it does now near Lares, it is believed that the several master streams crossing to the coast originated as extended consequents. The streams that may be so designated are the Arecibo, the Manati, the Plata, the Bayamon, and the Rio Grande. All of these have their sources far back in the mountains, and those in the western part, where the coastal plain is highest, have cut deep, vertical-walled trenches beneath its surface (Fig. 14). But it is only an assumption to assert that these trench-like valleys were formed in the ordinary way by direct

down-cutting. What seems more probable is that, though at the tim
their origin these streams flowed upon the surface, an underground
tem was soon developed along the buried valleys of the oldland.
ultimate collapse of the beds above the underground drainage lines
sulted in the well-formed valleys now trenching the coastal plain.

The Tanama River, a tributary to the Arecibo, still preserves a sub
ranean middle course and appears to follow a channel the complete
lapse of whose roof has not yet been effected. The main evidence in f
of this history of stream development is the fact that the old pre-Terti
valleys of some streams, as, for instance, the Camuy River valley eas
Lares, which were buried by the Tertiary deposits, appear to have b

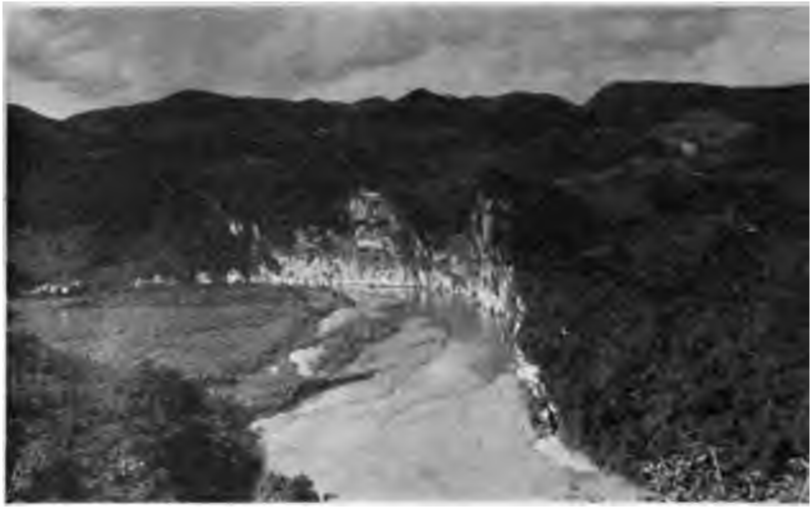


FIG. 14.—*The gorge of the Manati, incised below the surface of the coastal plain*

reoccupied by the present streams. This is to be noted where the strea
enter the cuesta face and pass from the stripped upper portion of
valley into that part still filled with limestone. It is inferred that
underground portions of such streams as the Tanama and the Cam
rivers are following the old buried valleys. These streams are similar
origin to the "resurrected" streams of the southern states described
McGee (1891). In the cases cited by McGee, however, the old vall
were covered over by only a shallow deposit and the streams upon
retreat of the ocean had no difficulty in finding their earlier channels.
the Porto Rico case the valleys were completely filled, and it was only
inability of the filling material to withstand solution by water seepi

along the buried channels which resulted in the resurrection of the original valleys. The Culebrinas River is another example of a resurrected stream. Its course appears to follow an old drainage line and cuts diagonally across the coastal plain formations, thus truncating several cuestas. Its tributaries have stripped away all of the Tertiary on the southern side of its valley except the few isolated remnants in the Aguada region. Part of its broad valley, therefore, functions as an inner lowland, but the stream itself can not be classed as a subsequent stream, at least in reference to the coastal plain. It was indeed originally subsequent if it is presumed that its course was determined by less resistant members of the oldland rocks.

Whether there are any streams to be definitely classed as initial consequents upon the coastal plain it is difficult to say, but presumably the Cedros as well as the shorter streams along the coast are examples. As for large, well-defined examples of typical subsequent streams developed on the coastal plain, one must doubt if there are any. Two tributaries of the Arecibo, the Caguanitas and the Limon rivers, might appear to hold such a position, for they flow at the base of a cuesta. But their gorges are cut so deeply into the older rocks as to make it unlikely that all this cutting took place in post-Tertiary time, especially since the limestone cuesta has retreated hardly any from their valley sides. It is more probable that these are also resurrected streams which have succeeded in regaining their old courses by the removal of the limestone which buried them. The best and about the only examples of subsequent streams developed upon the north coastal plain are the Guatemala and other minor tributaries to the Culebrinas between San Sebastian and Moca. These have been developed upon the Cibao limestone between the two cuestas, and have succeeded in opening out a large subsequent lowland, larger than any other lowland developed within the limits of the coastal plain. It is also believed that short east-west trending sections of the Guajataca River are subsequent in origin.

THE BELTED CHARACTER OF THE COASTAL PLAIN

The coastal plain on the north side of Porto Rico may be concisely described as a belted coastal plain gradually increasing in width from the east, where it occurs only in patches, to its broad western end. Let us amplify this picture by a description of each of the successive belts.

The inner lowland.—Normally the innermost belt of a coastal plain is its inner lowland. On the north side of Porto Rico an inner lowland extends eastward from Morovis. East of San Juan remnants of the coastal plain are almost entirely lacking, but the rolling coastal country all the way to Rio Grande and Luquillo is simply a continuation of the inner lowland further west. In reality this inner lowland is the stripped surface of the lower peneplane, which has already been described. It is therefore rather a part of the oldland than of the coastal plain. In places, however, it apparently still preserves remnants of the lowest coastal plain deposits. This is the case between Bayamon and Rio Piedras. Here the usual rolling surface of the inner lowland gives way to rather flat expanses of country. When these distinctly flat areas are dissected by streams, as, for instance, in the case of the Bayamon River, and further east as well, they have the aspect of alluvial terraces. The best preserved portions of these basal beds appear to be those areas closest to the remnants of the cuesta. Between Ciales and Lares no inner lowland appears and the inner cuesta rests upon the spurs of the rugged oldland. West of Lares the open lowland drained by the Culebrinas River system functions as an inner lowland. The Culebrinas River flows toward the northwest and truncates the east-west cuestas and belts of the coastal plain. Therefore its valley is not a true inner lowland. Rather, as previously stated, the river appears to have resumed its course on the oldland, which was buried by the coastal plain—that is to say, it is resurrecting its buried channel. The fact that its course follows the general strike of the older rocks and that it has no relation whatever to the weaker beds of the coastal plain bears out this interpretation.

The Lares limestone cuesta.—The southernmost or inner cuesta is developed upon the Lares limestone, a massive formation which gives rise to exceedingly rugged, hilly topography. The hills are close-set, 100 to 200 feet high, and dominate the cuesta from Lares to the region about Morovis, east of which point the main cuesta is somewhat less pronounced and more discontinuous. Where this belt exhibits its maximum width, in the Lares region, it is only about two miles wide and is the narrowest of the chief belts of the coastal plain. At Lares the cuesta face is a striking topographic feature, having in places an absolute elevation of about 1800 feet above sealevel. It stands 500 to 600 feet or more above the floors of the valleys at Lares, but where the cuesta rests upon the spurs of the oldland it has a face measuring only 100 to 200 feet in height. Throughout its extent the cuesta face cuts through the conical hills which happen to stand at its edge, and the resulting cliffs, exposing a cross-section of the almost horizontal white limestone, are perfectly vertical and usually bare of vegetation. From Lares to Ciales the cuesta has the same general aspect. Its crest-line is irregular and the white cliffs marking its front are conspicuous at long distances. Conical or irregular hills typify this belt. They appear to be the remnants of a continuous surface left after the collapse of underground cavities, brought about by the ready solubility of the massive limestone. The hills are always small in areal extent. The depressions between them are usually without drainage outlets. Toward the north the hills of this belt become lower and gradually disappear where the Cibao limestone, which is soft and shaly, overlaps them; but the tendency to form conical and irregular hills can actually be seen in the sides of valleys cut below the rolling country of the Cibao limestone into the underlying Lares formation.

The Cibao limestone lowland.—The next belt to the north is technically a lowland. Actually it has the aspect of a rolling plateau. This lowland belt is three to four miles wide and may be traced from between San Sebastian and Moca eastward to Morovis. In its eastern portion it appears to develop a series of minor cuestas, as may be seen in valley sides of the Manati River and along the Morovis road. The general aspect of this lowland belt, however, is that of a plain, sometimes deeply incised by streams, but almost always devoid of the numerous haystack hills which characterize the belts to the north and to the south. The limestone (Cibao limestone) making up this belt has a tendency to develop flat benches or terraces along the walls of streams which have cut below the surface of the plain. Benches of this kind are due to differential erosion upon the members of this formation and are distinct features in the walls of the valley of the Manati River. Two of these, an upper and a lower bench, the one standing a hundred feet or so above the other, are especially striking. They slope perceptibly toward the north, where they dip below the next higher hill-forming beds. The western end of this lowland belt between San Sebastian and Moca has been reduced by the Guatemala and other minor tributaries of the Culebrinas to a decidedly lower level.

The Los Puertos limestone cuesta.—The fourth belt consists of rugged and bold hills, limited on the south by a distinct cuesta face which looks down upon the lowland just described. It may be traced all the way from Moca to the Arecibo River. Further to the east the cuesta face becomes less defined, but the belt of hills persists. The formation responsible for this belt is the massive Los Puertos limestone. Its pure character has encouraged the development of caves and sink-holes. The depressions are much larger than those in the Lares belt and, as Hubbard has pointed out, frequently occur in a series trending toward the ocean, as if induced by well-formed underground drainage lines. The hills are high and rugged and angular in outline. Their aspect is often that of the *mesas* and buttes of the southwestern United States, especially where they are a little set apart from their neighbors. In the midst of the hills the broad, flat-floored depressions, sometimes several acres in extent, grass-covered, and walled in by high and ragged limestone cliffs, rich in the luxuriance of tropical vegetation, are picturesque in the extreme.

The Quebradillas limestone lowland.—Next to the north and extending to the coast is a broad lowland or plain, in large part undissected. Like the other lowland to the south, this one also has the aspect of a plateau because of the canyon-like nature of the stream courses which occasionally break its surface. It forms a belt five miles in width in the western part, becoming somewhat narrower and more diversified toward the east until the Arecibo River is reached. East of this point the uninterrupted plain-like character entirely disappears and the region is made up of haystack hills and intervening flat expanses. Hubbard has assigned the term Quebradillas limestone to the strata responsible for this topographic belt. At the western end of the island this rolling belt extends along the coast from Aguadilla around to Camuy in a fine stretch of wave-cut cliffs approximating 200 feet in elevation. Throughout most of their extent, however, the cliffs are at the present time protected against wave attack by narrow beaches. Between Hatillo and Arecibo the hilly back country slopes gradually seaward and the wave-cut cliff is usually not present. In the western part of this lowland belt, as in the region between Aguadilla and Isabella, shallow depressions or sinks, frequently holding small ponds, abound. Even when no water is visible, the fact that these depressions serve to collect water is attested by the presence of large trees growing in them. Elsewhere the landscape is open and presents the aspect of a rolling plain.

SPECIAL FEATURES OF THE NORTH COASTAL PLAIN

To divide the eastern portion of the north coastal plain, in general that part east of the Manati River, into belts such as have just been described is not expedient because the haystack hills become such prominent features throughout, whereas in the western part of the coastal plain the haystack hills were most numerous on the cuesta-forming belts and were infrequent on the intervening lowlands. In the eastern part of the coastal plain the entire country is characterized by the presence of the haystack or *pepino* hills.

There are two elements in the landscape (Fig. 15), the hills and the flats. Locally the proportionate area involving each form varies from 100 per cent hills to 100 per cent flats. Practically all the features of the limestone district owe their presence and form either directly or indirectly to the prevailing tendency toward underground drainage. Caverns and sink-holes form everywhere. At first the depressions are small in area, with rough, irregular bottoms and no outlets; but as further collapse of their walls takes place, and as the roofs of adjoining caverns give way, separate sinks become connected and the floors widen out and become flat. It may happen that the floors of adjacent depressions are not at the same level because the underground solution is controlled by more or less unevenly distributed shaly beds in the limestone. Berkey thus explains the discrepancy in level between adjacent depressions as well as the terraces which prevail where more extensive flat areas have been opened out between the hills. As the sinks widen, the angular-shaped hills remaining isolated upon the flat plains have a close resemblance in form to the *mesas* and buttes of the western United States. But when they are further reduced in size a softer outline is assumed and then they become typical haystacks, occasionally quite conical in form.

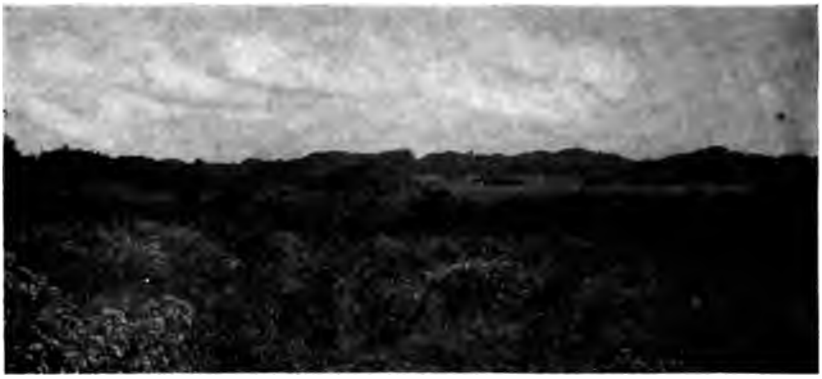


FIG. 15.—*Open haystack belt between Barceloneta and Arecibo*

One of the extreme stages, that in which the flat areas so predominate that the hills are only rare and therefore conspicuous features on a more or less level plain, is represented in the region around Bayamon. Between this point and Rio Piedras there are stretches of country exceedingly flat, at least in profile view, but they have suffered moderate dissection and often have the aspect of a terrace above the observer. Traced to the south, these flat expanses imperceptibly become more and more irregular and the rocks of the older series begin to outcrop. In fact, these flats merge with the rolling topography of the lower peneplane. Throughout this region and on the road to Guaynabo the flat tracts above the streams are planted in orchards of oranges and grape-fruit, and occasionally cultivated for pineapples. The description of the haystack hills and the accompanying flats just given for the eastern part of the coastal plain applies equally to those belts in the western part where the haystacks prevail. An unusual feature and one of more than ordinary interest results where the waves of the Atlantic have pushed back the high cliffs near Quebradillas to such a point as to bring the coast next to one of the open flats. A marine-cut terrace is thereby simulated (Fig. 16). The slope of the terrace surface is toward the north and conforms with the slight dip of the Tertiary beds. An observer noting this feature for the first time will immediately assume that it is due to wave planation, when the land stood at a lower level. But after having become familiar with the flat stretches described above, and having noted their characteristic development throughout much of the area immediately to the south of Quebradillas, he has no difficulty in assigning to the apparent wave bench a similar origin. If differential erosion has been the factor in forming this terrace, similar terraces would be expected along the sides of valleys cut in the Tertiary coastal plain. Such are to be seen in their [illegible]est development along the Manati River, and have already been described.

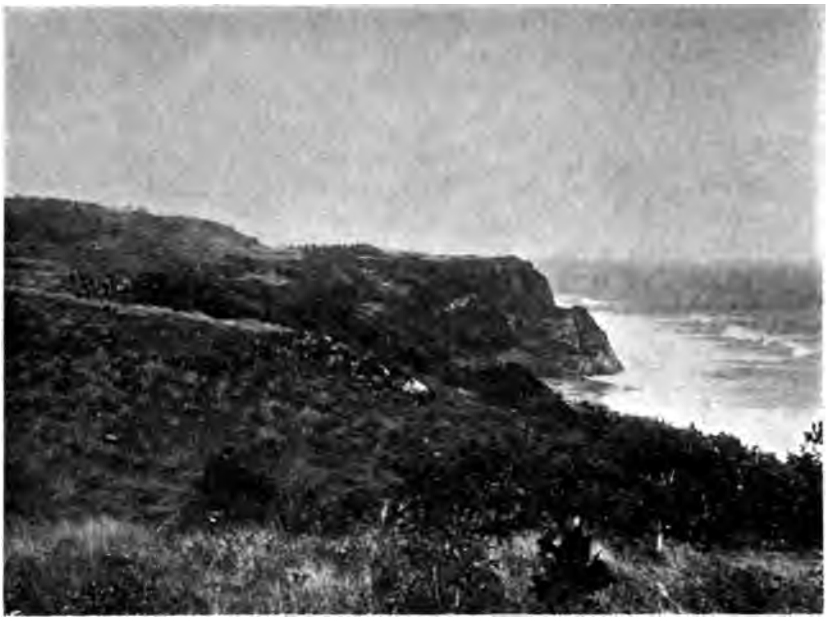


FIG. 16.—*Apparent wave-cut bench at Quebradillas*

It is due to differential erosion upon the almost horizontal beds of tertiary limestone. A very slight seaward dip is to be noted, conforming with the dip of the bedding.

ISOLATED REMNANTS OF THE TERTIARY

East of San Juan the remnants of the coastal plain are small and infrequent. There is a group of hills just east of the highway between San Juan and Rio Piedras, and an east-west trending row of hills northeast of Carolina, entirely surrounded with alluvial deposits. These are conspicuous features in an otherwise monotonous landscape, and their altitude, although inconsiderable, suggests that the coastal plain formerly extended much further south over the flat rolling country between Carolina and Rio Grande. Whether a greater amount of material has been stripped from the oldland in this eastern end of the coastal plain than in the western part it is impossible to ascertain; but it does not seem unlikely, inasmuch as there is a greater precipitation in the east.

THE SOUTHERN COASTAL PLAIN

Eastern portion, Juana Diaz to Yauco.—Even more than on the north side of the island, the coastal plain on the south has been cut into blocks by transecting streams. In the eastern part between Ponce and Juana Diaz the valleys of the streams crossing to the south are wider than the remnants of the coastal plain remaining between them. The coastal plain remnants stand up as isolated masses of hills, more or less flat-topped when seen from a distance, and with a gentle southerly slope. Their bases appear to be buried in the alluvium of the river flood plains. At close range the contrast between the steep cuesta front and the gentle back-slope is not evident, but from a commanding viewpoint the landscape resolves itself into the customary orderly elements of a maturely dissected coastal plain. There is good reason to believe that the Tertiary in the region between Ponce and Juana Diaz was laid down in a former bay in the oldland. The deposits filling the head of the bay have since been stripped away and their place partly taken with alluvium. The resulting flat-floored inner lowland looks like an estuary extending back into the foothills of the oldland (Fig. 17). The character of the deposits, which as noted by Berkey are more shaly in this region, is in accord with the assumption that the Tertiary beds were laid down in an estuary in the Juana Diaz region, an estuary which received the waters of the Jacaguas River. The streams coming down from the oldland have swift and turbulent courses, with frequent falls and rapids over rock ledges, until they emerge from their comparatively narrow valleys and flow out upon the flood plains of the open valleys in the coastal plain province.

Part of the city of Ponce is built on the southern slope of a block of Tertiary hills lying between the Portugues and Canas rivers. On its north side this block displays a well-defined cuesta face overlooking the inner lowland, which has here narrowed to a valley not more than a mile wide. At one point a distinct notch interrupts the face of the cuesta. Communicating with this notch on the back slope of the cuesta is a winding valley, now unoccupied by any stream. This valley was apparently formed by one of the extended consequent streams crossing the coastal plain. That it was occupied by a stream coming down from the oldland is attested by the fact that in its bed well-rounded boulders of the older rocks occur. This would suggest that the diversion of consequent streams has been effected by the subsequent drainage occupying the inner lowland.

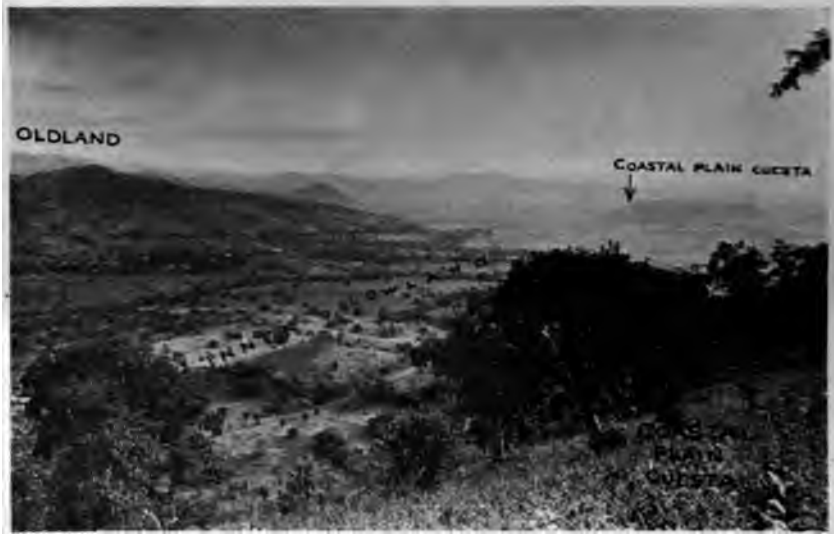


Fig. 17.—*The inner lowland of the south coast, looking eastward from cuesta face back of Ponce*

At the present time the floor of the inner lowland has been cut down 100 feet below the floor of the abandoned valley crossing the cuesta. Just west of Ponce the Tertiary remnants become much larger. The surface of the blocks, while having a general southward slope, is exceedingly irregular. The cuesta between Ponce and Peñuelas is usually very well defined, but, as previously demonstrated, the irregularity of the oldland surface upon which the Tertiary was laid down is occasionally accountable for a failure of the customary features.

The road from Ponce to Peñuelas runs for a considerable distance on the face of the well-defined cuesta, continuing thence along the inner lowland to Yauco. The cuesta is interrupted between Ponce and Yauco by the gorges of several extended consequent rivers coming from the oldland. At Yauco it loses its sharp character because erosion exposes the irregular oldland hills upon which it rests, though its face can be seen all the way to Guanica, where it becomes steep and imposing again.

Western portion, Guanica to Cape Rojo.—The topography in the region about Guanica has been previously discussed. It is interesting to add that in a minor way the coastal plain remnant southwest of Guanica displays a belted character. Two cuestas occur. The two ends of the small subsequent lowland intervening between the outer and inner cuesta are now drowned to form Pardas Bay on the east and Salinas Cove on the west (Fig. 10).

An idea of the fragmentary extent of the coastal plain in the southwest corner of Porto Rico may be gained from the map. All but the westernmost remnants show a distinct cuesta (Fig. 18). The Morillos de Cabo Rojo and the islands forming Point Aguila are low remnants of the coastal plain formerly cut off from the mainland as a result of drowning, but now attached to it by a beautiful series of connecting beaches.

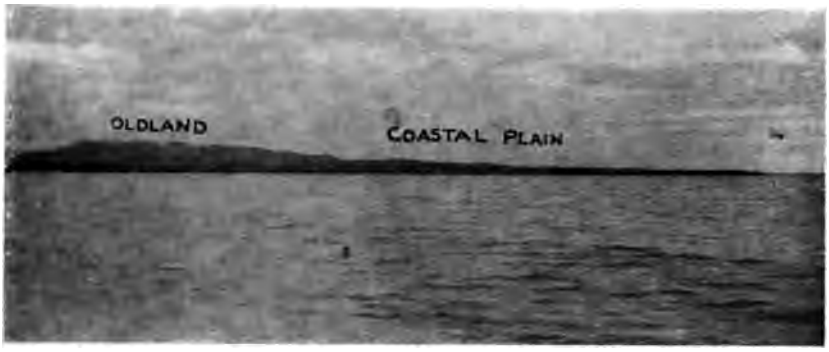


FIG. 18.—*The Tertiary coastal plain lapping upon southern flank of Mariquita Hill*
View eastward across Sucia Bay near Cape Rojo.

Sink-holes and the question of assumed faulting.—The question of underground drainage and the sagging and collapse of cavern roofs acquires undue physiographic importance because the resulting deformations of strata have been ascribed by Berkey to major faulting. Several lines of evidence have been cited by Berkey as seeming to favor faulting between the Tertiary and older series on the south coast. They have been briefly presented and discussed. It is the intention at this point, however, to dwell more thoroughly upon the matter of "crush zones, slight folding and drag," noted by Berkey in the strata of the coastal plain near

Peñuelas, and the pronounced tilting of the beds a mile southwest of Juana Diaz. The desire here is to show that these deformations are all local in character and are due to the sagging and bending of strata during the formation of sink-holes.

Sink-holes are of common occurrence on the south coastal plain. The cuesta face between Peñuelas and Ponce and much of its back slope is surmounted by hummocky and conical hills, suggesting in some degree the hills on the cuesta front at Lares. Depressions without outlets are common. There are also many large depressions which serve as continuous drainage lines for insequent as well as for consequent streams, and appear to have been originally subterranean channels. Abundant sink-holes and haystack hills are characteristic of the region between Ponce and Peñuelas (Fig. 19).

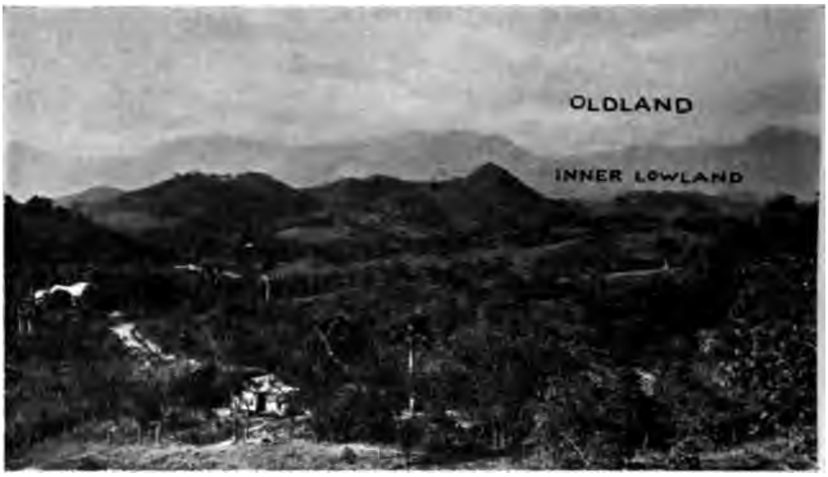


FIG. 19.—*The surface of the coastal plain between Ponce and Peñuelas*

Showing the haystacks and sink holes which characterize it. View looking north toward the mountainous oldland.

Careful observation of the dips of the limestone along the road between Ponce and Peñuelas lead to the following generalizations, which appear to be well founded:

1. The dips have no uniformity in direction and are constant only for very short distances, although the general dip of the formations is to the south.
2. The local dips are invariably toward a depression.
3. The dips along the cuesta front are just as variable as elsewhere and for the same reason.

4. The angle of dip is rarely over 10 or 15 degrees. Where the sink-holes are large the dips are gentle, but the tilt of the beds may be very marked where the depression is only a few yards across.

The usual appearance of the gentle dips is shown in Fig. 20, a view near the cuesta front at K 9.5-6 on the Ponce-Peñuelas road, looking northward toward the oldland. The dip here is 9 to 10 degrees toward the north, a direction not compatible with the idea that the older series had been faulted up. The dip in this case is toward the center of a large depression. In the field its relation to the depression is readily noted.

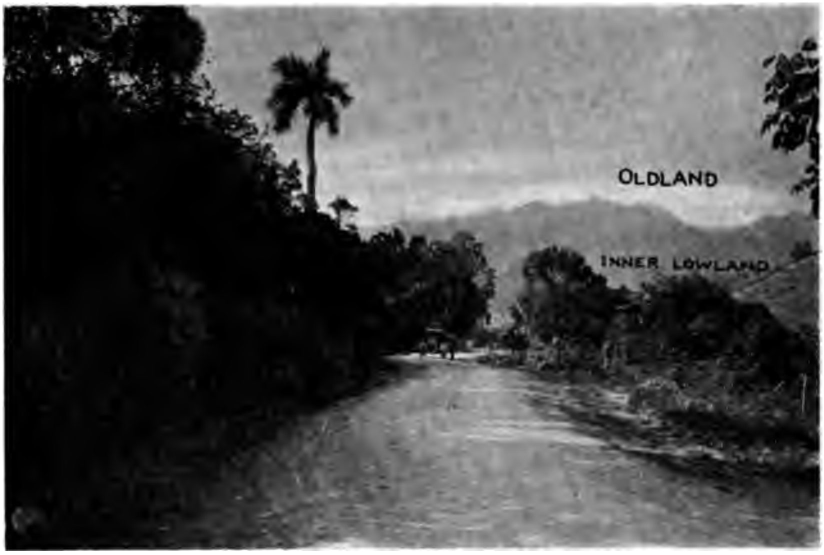


FIG. 20.—*Beds of the coastal plain dipping slightly toward the oldland*

Near cuesta face (K 9.5) on the Ponce-Peñuelas road, looking toward the oldland. The dip of the strata is due to a sink-hole depression.

Let us now turn to several localities which deserve closer attention. The first of these is near K 10 on the Ponce-Peñuelas road. Here the Tertiary beds lie in a highly tilted position upon the older series, as if they had been dragged into that shape by an upheaval of the older rocks. Perhaps the best way to acquaint the reader with the situation and at the same time present the writer's interpretation of the facts is to refer to the accompanying diagram, which is drawn from sketches made in the field (Fig. 21). The interpretation is comparatively simple. The collapse of a cavern has taken place just at the point where the Tertiary rests upon one of the hills of the older series. This is to be expected

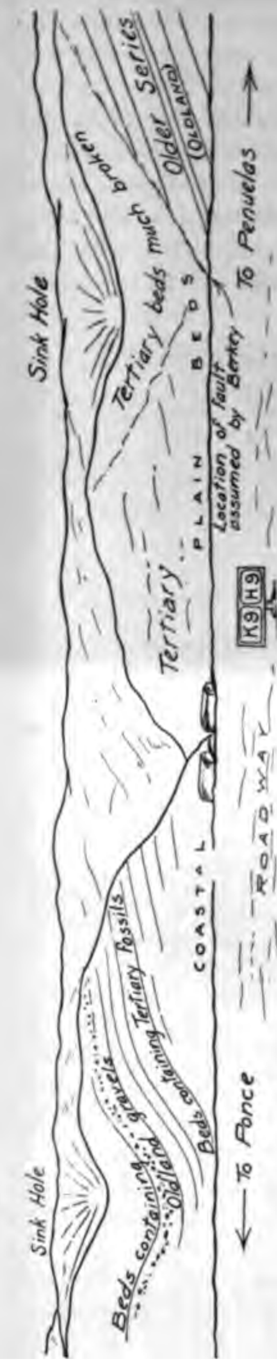


FIG. 21.—*Road cut at K 9 H 9 on the Ponce-Peñuelas road, showing relation of Tertiary to older series.* The Tertiary was deposited against an oldland hill at the right. The apparent faulting is due to collapse of sink holes, thus deforming the strata and giving the effect of "drag."

along the contact because here underground drainage is likely to be concentrated. As collapse took place the Tertiary beds were dragged down, simulating in every way true faulting. The extent of the slipping at this particular point is extremely local, not more than a few feet. The whole phenomenon, without the presence of the oldland hill, is duplicated a few feet to the south, as shown in the diagram. Throughout this section, as elsewhere, layers of older series gravels alternate with the fossiliferous beds of the Tertiary limestone. This suggests that during the deposition of the Tertiary the erosion surfaces of the oldland were in close proximity, such as would be the case if the Tertiary were laid down upon an irregular topography. The abrupt transition, therefore, from the Tertiary to the oldland is rather to be expected.

A second locality deserving particular attention is along the Jacaguas River, just a mile southwest of Juana Diaz. An almost vertical cliff has been cut by the river in a high hill of Tertiary beds. Some of the beds are highly tilted, showing dips of 30 to 35 degrees. Because this occurrence is not far from the line of the assumed fault, Berkey is inclined to believe that the apparent uptilting of the Tertiary strata is due to the disturbance of faulting. A careful study of this locality, however, leads me to ascribe the pronounced local dip of the beds to the collapse of cavities. This resulted in the formation of sinkholes on the surface of the ground. In this locality a cross-section of one of the sink-holes is provided, and it is to be noted that the beds dip toward the center of the depression (Fig. 22). The variation in dip from place to place along the section, sometimes toward the north and sometimes toward the south, would seem to suggest that the dip is due to local causes. Since it is evident that variations in dip, at least occasionally, may be brought about by the bending of strata beneath a sink-hole, it would appear unsafe to use the occasional southward dip as evidence of a major fault. Moreover, north of the section cited—that is, between it and the position of the assumed fault—the beds flatten out and become horizontal. In addition it is worth while to note that Berkey estimated a great thickness for the Tertiary at this point. He states that "for considerable distances an average dip of 30 to 36 degrees was estimated and the total thickness represented, based upon the width of the belt, must be at least 3000 feet." With this estimate I am unable to agree, and am therefore inclined to reduce the figure to approximately 500 feet, or 600 feet at most.

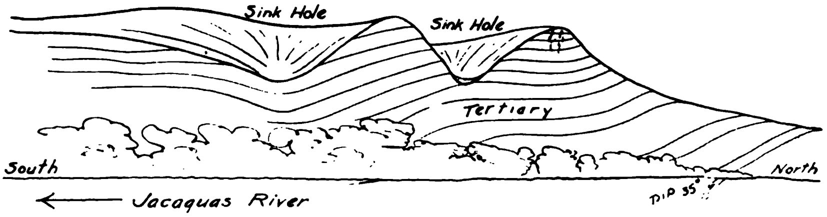


FIG. 22.—*Section of hill along Jacaguas River one mile southwest of Juana Diaz*
The variations in dip are due to collapse of sink holes.

VIEQUES

The dissection of the coastal plain on Vieques has resulted in a well-defined though small cuesta at its eastern end and on the south coast. Parts of the inner lowland have since suffered drowning.

RECENT SLIGHT SUBMERGENCE

GENERAL

Most of the coast line of Porto Rico shows evidence of recent submergence. However, many of the bays which resulted from the drowning of stream valleys have since been filled with alluvium. Indeed, the great alluvial plains bordering the lower courses of the rivers constitute not only one of the most striking and characteristic features of Porto Rico, but also one of the island's most valuable assets; for it is upon these extensive level tracts that the majority of the sugar-cane is grown. The term playa as used in Porto Rico refers to these plains. In general, the activities of each plain center in an important village built upon it, as, for instance, Fajardo, Naguabo, Humacao, and Yabucoa. The seaports for these villages are, respectively, Fajardo Playa, Naguabo Playa, Humacao Playa, and Yabucoa Playa, and in these cases the term playa is used in its true etymological meaning, referring to the shore. Bays not yet filled with alluvium are the exception and are to be found only in those situations where there are no large rivers to bring down material to the sea. This is especially true on local extremities, as in the northeast part of the island on San Juan Point. It is usual, however, to find such bays cut off from the ocean by a bay-mouth bar.

That the drowning occurred since the dissection of the Tertiary is evidenced by the drowned inner lowland and the drowned subsequent valleys eroded in the Tertiary coastal plain, as in the Guanica region and on Vieques. The effect of drowning is to be noted at the east and west ends of Porto Rico much more than on the north and south coasts. There are a number of reasons for this. First, the old subsequent valleys developed along the general east-west strike of the older series rocks are much wider and are opened out much farther inland than those formed by the north-flowing or south-flowing streams. Examples of such valleys are those of the Fajardo, Rio Blanco, Humacao, and Yabucoa at the east end of the island and the Culebrinas, Añasco, and Guanajibo at the west end. In the second place, the large alluvial deposits of the north and south coasts have buried many irregularities and have pushed the shoreline so far seaward as to disguise the effects of drowning. Third, the dissection of the Tertiary coastal plain on the north side resulted mainly in narrow valleys or left much of it intact so that slight submergence did not appreciably alter its outline.

EAST COAST

San Juan Point is the most northeastern promontory of the island. It is really a complex tombolo. Owing to the scarcity and small size of the streams, the bays which have been cut off from the ocean by long sand beaches have not been entirely filled with alluvium and the drowned aspect of the coast is thus somewhat preserved. The entire east coast of Porto Rico, from San Juan Point to Yabucoa, presents the usual features indicative of drowning, an irregular shoreline, characterized by promontories and islands. The general appearance of this part of the coast may be gained by noting Fig. 23. Along the stretch of coast in the southeast corner of Porto Rico between Yabucoa and Maunabo the valleys which suffered drowning were very small and have since become clogged with alluvium. The headlands, and the alluvium deposits as well, are being cut back by the waves.

SOUTH COAST

The south coast from Patillas to Ponce is made up of low alluvial flats or else the edges of alluvial fans trimmed by the waves, so that what earlier evidence there may have been of drowning is now lost. There are occasional hills, as, for example, at Central Aguirre, now entirely surrounded by alluvial deposits. These doubtless were islands immediately after submergence. West of Ponce the submergence affected not only some of the subsequent valleys between the cuestas of the coastal plain, but also parts of the inner lowland. Guanica Lake is apparently a drowned portion of a broad valley or lowland in the oldland itself. It has since been cut off from direct communication with the sea by the deposits of the Susua River. Guanica Harbor is a part of the drowned inner lowland (Fig. 10) and Pardas Bay, as well as Salinas Cove, near Guanica, are parts of a drowned subsequent valley. Guayanilla Harbor apparently has a similar origin. The region about Parguera on the southwest coast exhibits further evidence of drowning in the peninsulas and islands of the oldland. The Morillos de Cabo Rojo represent parts

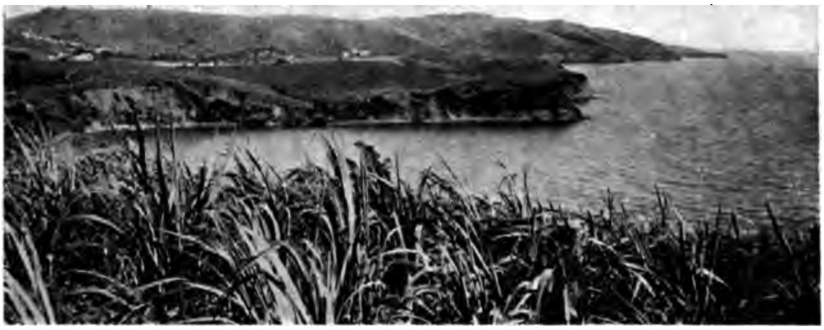


FIG. 23.—*The drowned coast of eastern Porto Rico*

View north of Fajardo, looking toward San Juan Point. Most of the headlands have been cliffed by the waves.

of the coastal plain detached as a result of submergence, but now connected with the mainland to form a complex tombolo of rare beauty.

West Coast

The west coast of Porto Rico is in many respects similar to the east. The three largest rivers—the Guanajibo, Blanco, and Culebrinas—emerge from the hills upon extensive flood plains, which are apparently alluvium-filled estuaries. Boqueron Bay still displays rather distinctly its drowned character. Whether the drowning affected the entire valley from Boqueron to Guanica it is impossible to assert definitely, but it seems very likely that this was the case. Though most of the valley floor is now spread over with alluvium, it is very low and swampy, and the wells put down through the alluvium yield water of a distinctly saline character. The divide between Guanica Lake and the marshes draining westward to Boqueron Bay is low and in times of heavy rains covered with water, so that even now a very slight rise of sealevel would effect a junction between Guanica and Boqueron bays (Fig. 5). North of Boqueron Bay the west coast is only moderately irregular, but this is because the bays have to so large an extent been filled with alluvial deposits.

North Coast

Along the north coast of Porto Rico evidences of embayment are not striking.

Theoretical Considerations

AMOUNT AND CAUSE OF SUBMERGENCE; GLACIAL CONTROL

Vaughan (1916) has made a study of the Virgin and Leeward Islands and St. Thomas, to the east of Porto Rico, as well as of other West Indian islands, and concludes from an investigation of hydrographic charts that the recent submergence in this whole region has been approximately 20 fathoms. He notes also that "there is in the Virgin Islands and in Cuba clear evidence of a lowering of sealevel by about 20 fathoms, perhaps more, previous to resubmergence." He states in addition that in other places, as, for instance, off the north side of St. Thomas, the west side of Anguilla, the southeast coast of Antigua, and Mosquito Bank off Nicaragua, the similarity of submarine profiles suggests that a lowering of sealevel preceded resubmergence. What caused this lowering and subsequent rise of sealevel? To cite Vaughan again: "As it affects a large area, it appears too widespread to be explained by local crustal movements. The changes in position of strand line here noted are more reasonably explained by a lowering of sealevel due to the withdrawal of water in the Pleistocene ice epochs to form the great Continental glaciers and the raising of sealevel after each epoch through the melting of glaciers." The amount of drowning, 20 fathoms, proposed by Vaughan, agrees closely with Daly's estimates (1915) of the rise of sealevel due to ice melting.

SUBMARINE PROFILES EAST OF PORTO RICO; ORIGIN OF CORDILLERAS REEFS

A submarine profile just east of Porto Rico reveals a sea floor under Vieques Sound standing at a depth of 8 to 16 fathoms. Much of it is flat, but it appears to be made up of different levels or terraces. To the north of the Cordilleras Reefs and Culebra Island there is a second flat area or bench 5 to 10 miles in breadth. This stands approximately 30 fathoms below sealevel and is separated from the higher level to the south. just described, by a distinct break or submarine escarpment. Upon this escarpment stands the east-west trending chain of islands known as the Cordilleras Reefs. Vaughan has expressed the opinion that the outer bench represents a surface reduced by marine planation during the last period of maximum glaciation when the sealevel was lowered some 20 fathoms and then submerged. The escarpment he considers a wave-cut cliff marking the southern edge of this bench. As for the apparent terraces on the shallower flats to the south, Vaughan suggests that they may have been formed as a result of oscillations in water level during the different glacial epochs, or in places they may represent submarine terraces being formed at the present time. The depth of the outer platform, as before stated, is approximately 30 fathoms. This depth below sealevel Daly (1915, p. 182) estimates as the present position of platforms cut and built by the waves during maximum glaciation. The essential line of reasoning as to how this present depth was brought about is as follows: It is assumed that in weak materials open-ocean waves can quickly form a bench about 10 meters below low-water level, but that abrasion in greater depths is infinitely slower; that in the course of 50,000 years the depth of the bench surface would probably not be increased to more than 20 meters or roughly 10 fathoms. It is also assumed, after careful estimates, that the maximum lowering of level in the tropical ocean during the Pleistocene was 30 fathoms below present sealevel. This amount added to the 10 fathoms cut by the waves would leave the bench surfaces now 40 fathoms below sealevel as a maximum. Variation in the strength of the wave attack in different localities and in the character of the material eroded, as well as in other factors, would account for the slight variation in the present depth of the benches. As a rule, a depth of 30 fathoms would be the average.

No other theory has been proposed which so well accounts for the approximate accordance in level of submarine benches at a depth of 30 fathoms the world over. And there is apparently no other way to explain the escarpment marking the inner margin of the platform than to assume that it is the wave-cut cliff cut during the time the platform was being beveled. From the crest of this escarpment rise the Cordilleras Reefs. This line of reefs may be explained as a range of dunes capping the escarpment and formed of the material cut from the platform during its erosion in Pleistocene time. The summit of the ridge in its highest points rises some 50 to 60 feet above the escarpment on which it stands. The bed rock making up this platform is apparently Tertiary limestone, although no limestone outcrops on the immediate mainland. There is a marked cross-bedded structure of the limestone material composing the islands, and in general aspect they suggest dune formation. If the glacial-control theory is accepted, then it must be assumed that the top of the escarpment stood slightly above sealevel during the Pleistocene. Dune formation was therefore possible. In the western part of Porto Rico dunes of similar height are now forming. The Cordilleras Reefs appear to be the eastern expression of the San Juan formation occurring on the mainland.

RECENT CHANGES

The changes which have been effected in Porto Rico since the period of drowning, though all going on simultaneously, can be most clearly treated as separate topics. They involve the following events or processes:

The deposition of alluvium in stream valleys, in drowned bays, and as alluvial fans on the south side of the island.

Wave and wind work.

A probable slight emergence.

Alluvial Deposits

Extensive alluvial deposits form broad plains known as playas along the lower courses of most of the rivers of Porto Rico. These deposits, especially those on the east and west ends of the island, apparently fill estuaries caused by drowning. In the case of the Fajardo, Naguabo, Blanco, Yabucoa, and Maunabo rivers on the east coast and the Guanajibo, Mayaguez, Blanco, and Culebrinas on the west coast, this relationship is distinct. Undoubtedly portions of these plains are flood plains developed by the widening out of the lower courses of the rivers. The surface of the alluvial plains along the lower river courses grades into the surface of the terraces which occur further upstream. During excessive rains the rivers overflow much of the playa areas. There, old courses, meanders, and other usual features of flood plains are to be observed. In occasional instances the rivers bring down sufficient sediment to extend the flood plain forward into the sea as a delta. But this occurs only in protected places where the waves and currents along shore are weak. The Fajardo River entering Vieques Sound appears to be a case in point.

Along the north and along the south coast the alluvial plains extend as a broad strip parallel with the coast rather than as estuarine fillings. However, there is a distinct contrast in the aspect of the alluvial deposits of these two coasts. The north coastal stretches are low and swampy. The plains on the south side stand considerably above sealevel. Along the north coast the deposits are often typical flood plains with almost horizontal surfaces. The deposits on the south coast are more truly alluvial fans with a pronounced seaward slope. Practically all of the low north coast is fringed with barrier reefs. The waves of the south coast, however, have thrown up no such reefs; there the àlluvial plains pass imperceptibly into the mangrove swamps along the shore, which shallows out for long distances, and only in one or two places, as, for instance, south of Guayama, have the quiet waters of the Caribbean cut away the non-resisting alluvium to form low cliffs.

Occasional observers have suggested that the low plains bordering the coast of Porto Rico, as also on other West Indies islands, represent a sea floor recently uplifted. It is true that in isolated places there is evidence of recent uplift in Porto Rico to an extent of 20 or 30 feet. On the other hand, it is rather certain that these coastal deposits are not of marine origin. Old stream channels filled with gravel, combined with angularity of the boulders, lack of assortment, and poor bedding, indicate that they are alluvial fans deposited by streams.

Most of the streams flowing across the alluvial plains of the south coast usually carry very small volumes of water. "Owing to the infrequency and small amount of the precipitation and the relatively porous character of the soil reducing the percentage of run-off, as well as the smallness of their catchment basins, they discharge minimum volumes of but 50 to 100 second-feet" (Wilson, 1899). In time of flood, however, they attain maximum discharges of nearly 10,000 to 20,000 second-feet, almost equal to that of the maximum of the larger northward-flowing streams. In the drier season of the year, during the months of January and February, even the larger streams of the southern coast do not flow through on the surface. Their boulder-strewn channels are marked here and there by pools of water, and it is a common thing to find that during these periods the extemporized trails and roads of the natives follow the stream beds, which occasionally lie as much as 20 to 30 feet below the general surface of the plains. In their lower courses the rivers are not confined by such high banks and nearest to the coast they flow on the surface of the flood plains (Fig. 24).

None of the deposits along the coast west of Ponce can be classed with the alluvial fans just described. They are typically flood plains filling broad valleys and terminating apparently in delta deposits.

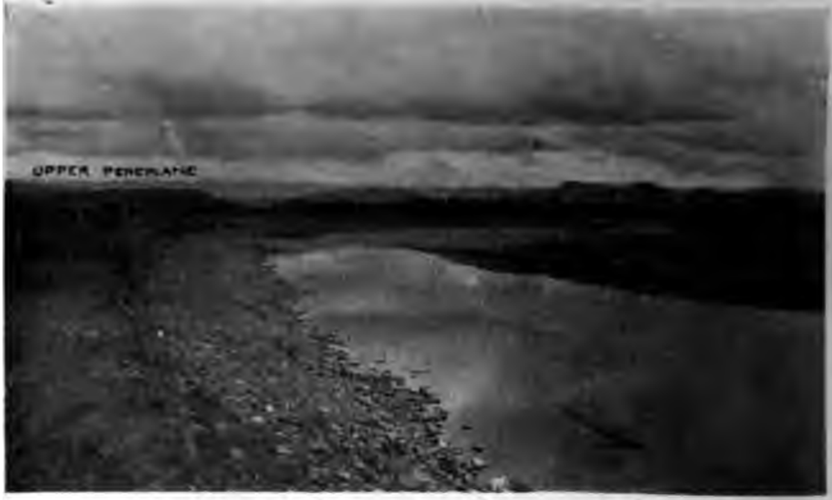


FIG. 24.—*Lower course of the Descalabrado River during the dry season*

This is one of the southward-flowing streams east of Ponce, all of which are subject to great variation in volume. In the distance appears the even skyline of the Porto Rico upland.

Perhaps brief mention should be made of the coarse wash from the hillsides in the southeast and southwest corners of the island. This constitutes very local features, although similar deposits were observed along the northern margin of the Boqueron-Yauco Valley. Deposits of this type occupy a position intermediate between talus accumulations and true alluvial fans.

Terraces are almost universal features along the Porto Rico rivers. Even well upstream, sometimes actually in the headwater portions, alluvial deposits occur. Except on the broad plains near their mouths the streams are now cutting well below the original surface of the alluvium.

The resulting terraces are occasionally 100 feet or so above the stream. The terraces of the Plata River may be cited as a striking example (Fig. 25). Just at the mouth of the gorge (near K 13 on the Comerio road), where the river emerges from its course through the upland, they may be easily visited. Their elevation above sealevel is about 290 feet, some 100 feet above the surface of the river. Their surface apparently slopes downstream and becomes continuous with that of the alluvial deposits of the north coast. In the alluvial-covered Caguas lowland terraces are common features. Perhaps the finest are those along the Gurabo River.

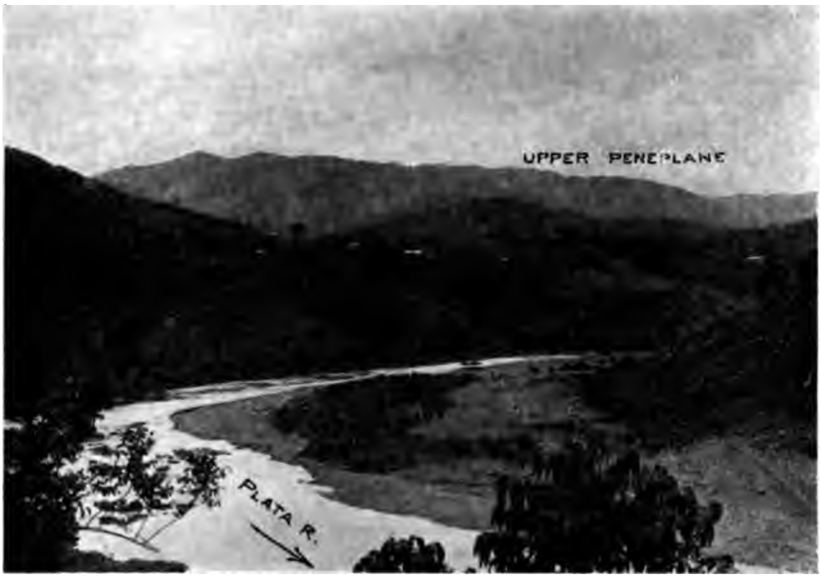


FIG. 25.—*The high terrace of the Plata River at K 13 on the Comerio road*

This terrace is over 100 feet high and dies out upstream, where the valley becomes narrow and gorge-like.

Most of the flood-plain surface of this lowland is out of reach of any present-day floods and seems to record an earlier period of more active deposition.

All the streams entering the east coast have broad flood plains which grade upstream into high alluvial terraces. This is true of the Fajardo, the Rio Blanco, and the Humacao. Some of the best-formed terraces on the island were seen along Peña Pobre Creek, a tributary to the Rio Blanco above its main flood plain (Fig. 26).

The terraces of the Coamo River and its branches, on the south side of the island, are more readily observed than those of most of the other streams in Porto Rico. East of Coamo the military road follows the Cuyon River, a valley deeply filled with alluvium, into which the stream is now incising itself. The town of Coamo stands upon a distinct terrace and the road from Coamo to Coamo Springs runs on the top of a terrace. At Coamo Springs Hotel several terraces may be seen. The lowest one, upon which the hotel is built, stands 100 feet or so above the river. The main valley of the Coamo River above the town of Coamo is heavily filled with alluvium. In cutting into this material the stream has in several places superposed itself upon hard rock ledges and this has resulted in pronounced waterfalls.

The steep gradient attained by the alluvial deposits on the south side of Porto Rico may be appreciated by the fact that in the upper valley of the Jueyes River, less than three miles back from the coast, the surface of the alluvium which fills the subsequent valley behind the Coamo limestone ridge stands almost 500 feet above sealevel. The slope seaward is sufficiently pronounced to be detected by the eye, though it is difficult to read with an ordinary clinometer, since it amounts to only one or two degrees. The upper branches of the Jueyes River have cut down very deeply into this alluvium, producing in places miniature canyons, which are distinct hindrances to cross-country travel. The upper course of the Guanajibo between San German and Sabana Grande and the Rio Blanco east of Añasco provide examples of terraces in the western part of the island.

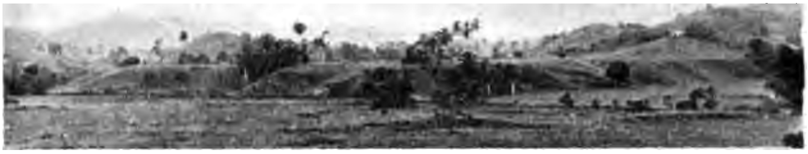


FIG. 26. —*Alluvial terraces of the Peña Pobre Creek, west of Rio Blanco crossing*

The smallest, but in some ways the most striking, of the alluvial deposits of Porto Rico are those clogging the short, open valleys in the southeast corner of the island between Maunabo and Yabucoa. These valleys head back only a mile, or even less, from the coast and are separated by headlands subject to wave attack. The surface of the alluvium is exceedingly steep and is now only in the initial stage of dissection. Along the shore these deposits are terminated by low cliffs 20 feet or so in height, which are usually fringed with a narrow beach. The alluvium is entirely the result of wash from the granite hills, whose slopes are covered with a very deep residual soil, granular in texture, but so firmly held together by its lime content as to be extremely brittle and ringing like cast iron under the hammer. The walls of the streams in the alluvium, like the sides of the gullies in the granitic soil, maintain an almost vertical attitude.

Two explanations may be offered for the development of terraces in Porto Rico, which, however, are not incompatible with each other. The first one suggests that the recent slight uplift of the island rejuvenated the streams and caused them to incise themselves below the flood deposits formerly laid down. The evidence of uplift, to be presented later, hardly justifies assumption of an uplift greater than 20 to 30 feet, and this is insufficient to account for the high terraces everywhere observed. According to the second explanation, the streams of Porto Rico have changed in general from aggrading streams to degrading streams, without necessarily any change in the relative position of land and sea. In the streams of New England such a condition is recognized. During the end of glacial time the rivers were heavily charged with debris and accordingly filled their channels with alluvium. But when the ice-sheets ceased to provide material for the streams to carry, their preglacial vigor was regained and terraces were formed as they cut down into the alluvium. We do not know just what causes may have contributed to the earlier overloading of the Porto Rico rivers. It is not unreasonable to think, however, that during glacial time climatic conditions in Porto Rico were different from those of the present. Not that any glaciers existed there, for there is no evidence of this, but it is conceivable that a heavier rainfall prevailed. Such a climatic condition is thought to have accounted for the ancient Lake Bonneville in Utah. In Porto Rico a prolonged period of heavy rains, though adding to the actual volume, would at the same time overload the streams with sediment. The rapid run-off makes almost every drop of rain that falls an active erosional agent, and because the effectiveness of the erosion is not in direct proportion to the run-off, but increases at a much greater rate, the tendency is therefore toward an overloaded condition of the streams below the steeper headwater portions. Increase of rainfall at the end of the glacial period would therefore add greatly to the load of the streams and cause aggrading of their courses where the slopes were modest. With the dying-out of these conditions degrading would again come into play until the stream profile prior to glacial times was restored. Terraces thus formed would grade into the present flood plains of the lower river courses.

WAVE AND WIND WORK

CAPE SAN JUAN REGION

Wave attack on Porto Rico has been much more effective on the north than on the south coast. In brief, it may be said that wave action has resulted in the development of marine cliffs throughout much of the northern coastal plain region, bay bars and cliffed headlands in the drowned oldland portion of the east and west coasts, barrier beaches and the consolidation of sand dunes to form the so-called San Juan formation on the north coast. It is believed that the subject can be best presented by means of a regional description.

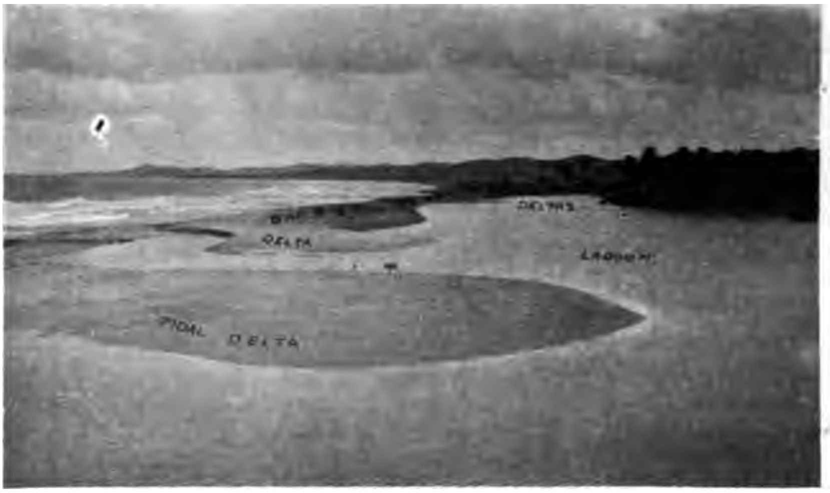
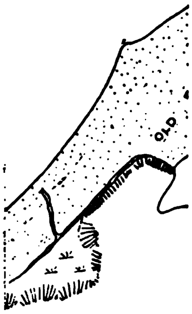


FIG. 28.—*Tidal deltas at Luquillo*

Formed behind a bar which has been built across the mouth of several confluent streams.

COAST OF THE CAPE SAN JUAN REGION

The coast of Porto Rico between Luquillo and Cape San Juan may be described as a shoreline of submergence in the submature stage of development. The headlands have been cut back, bars have been built across the bays, and the contour of the coast line is becoming approximately straight. Many of the bays have been entirely filled with alluvium: others remain as open lagoons. A sketch map of the region (Fig. 27), based on a rough field sketch, is serviceable in indicating the salient features. The successive building of bars nearer the mouths of the bays so as to form a succession of lagoons is well shown in Yegua Cove. Already



FAJARD

two bars have been built near its head, thus forming two lagoons, and at the present time a third bar is forming across its mouth. The cliffing of the headlands, in sympathy with the successive bars which are strung across between them, is a feature frequently observed, and is especially notable at Point San Diego. Attention has already been called to the fact that the bays receiving the larger streams have been completely filled with alluvium, whereas on Cape San Juan peninsula, where the streams are small, open lagoons still remain. Most of the beaches show interesting minor features in the form of tidal deltas either built out into the lagoon, as at Luquillo (Fig. 28), or almost buried under the later deposits of alluvium.

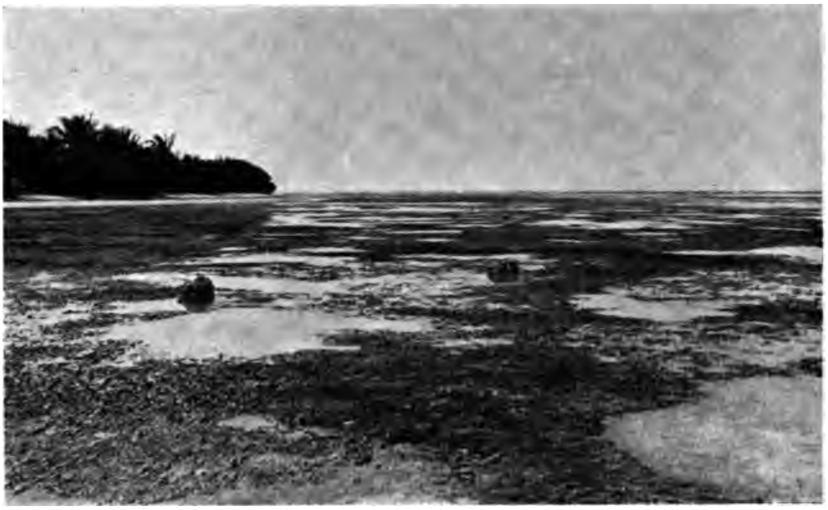


FIG. 29.—*Tidal flats just east of Point Embacaderos*

In the pools, corallines and branching forms of Porites grow. Occasionally large masses are torn up by the waves.

Beach ridges are common in this region. Just west of Luquillo at least ten parallel ridges were counted, each having a height of about five feet above the intervening swales. These ridges are extremely difficult subjects to bring out clearly in a photograph. The succession of parallel ridges shows that the coast line has advanced seaward. Just offshore the water is extremely shallow. At low tide, although the range in water level does not amount to more than one or two feet, considerable areas of tidal flats are exposed, such as may be seen just east of Point Embarcaderos (Fig. 29).

Wave action upon the headlands serves to emphasize the system of joints which are so well developed in the oldland rocks, especially in this northeastern corner of Porto Rico. Here, as on Culebra and its near-by islands, the cliffs are featured by sharp clefts along the prominent joints which in general trend in a northeast direction (Fig. 30).

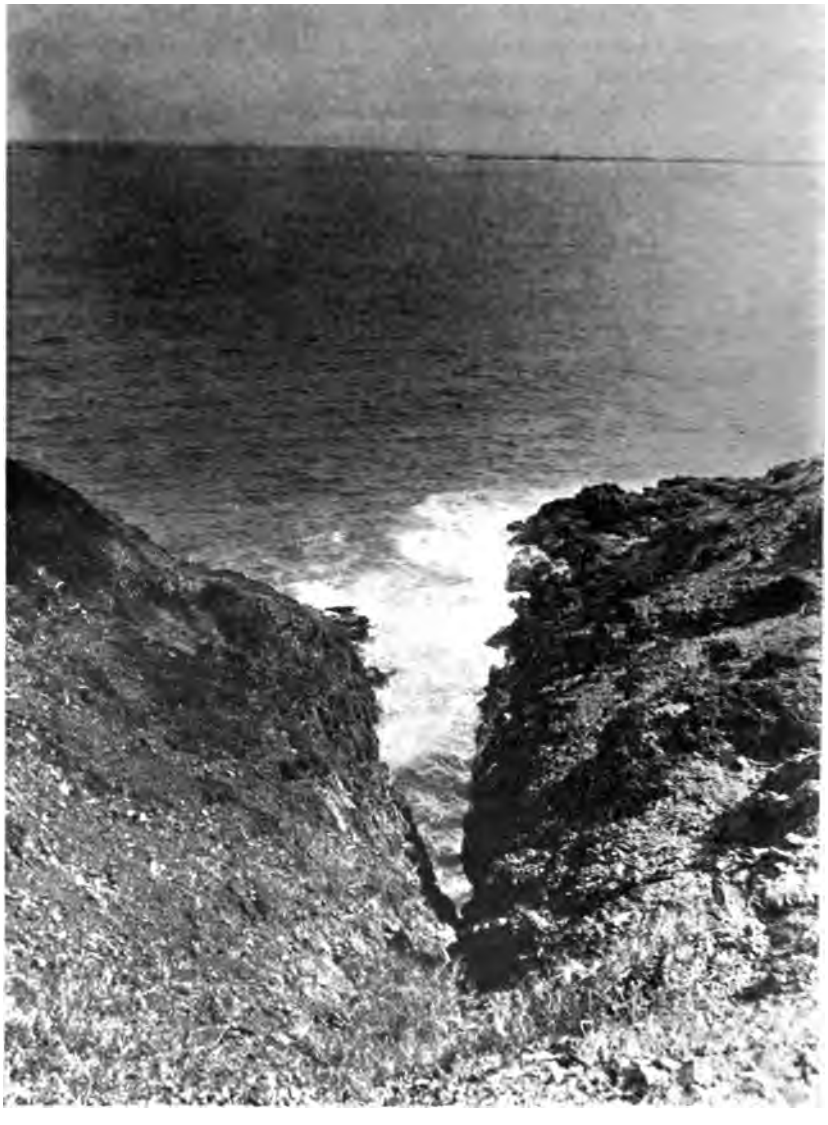


Fig. 30.—*Wave action along joint plane, San Juan Point*

In the distance part of Cordilleras Reefs.

EAST COAST

The long, palm-fringed beaches strung between the headlands of the east coast constitute one of the most picturesque features of this part of the island. The former bay or lagoon cut off from the sea by the beaches has in most cases become filled with alluvium, and the extensive flat tracts or playas which result have already been described. They constitute the great and fertile sugar lands of the island. In general, the beaches are made up of a succession of obscure ridges and are covered with groves of cocoanut trees, which in a distant view contrast strikingly with the cane lands behind them. The promontories are always undergoing wave attack. Occasionally older cliffs may be seen, now protected by a tract of sandy beach.

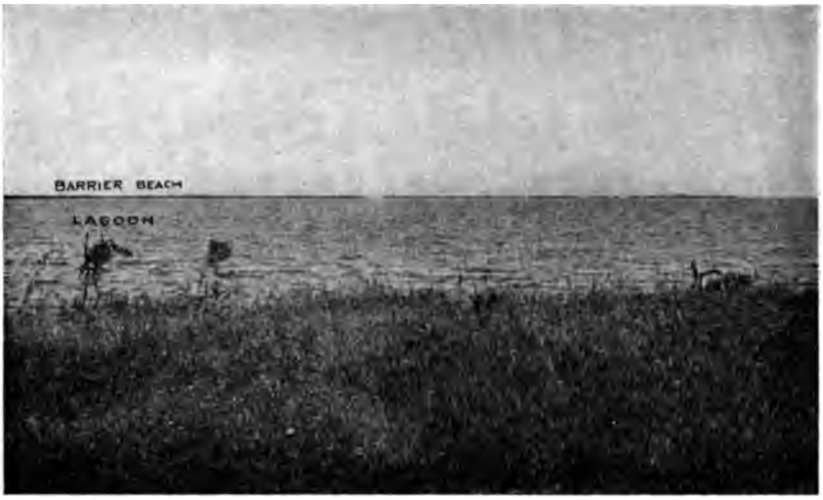


FIG. 31.—*The Caribes Islands*

An offshore bar cutting off Jobos harbor from the Caribbean.

The smaller streams flowing upon the playas, especially during low stages, find their outlets to the sea blocked by the bars just described, but the larger streams are able to maintain an opening through them. All of the water-courses bring down much fine material which, if it is carried out in front of the bar, serves as a supply for the storm waves when they come to throw up another beach. Occasionally, when the supply of alluvium is excessive, or the waves and currents are not sufficiently vigorous to dispose of the material carried through the bar, it is dropped to form a delta. This is the case at the mouth of the Fajardo River, as is readily appreciated by an observer on one of the hills overlooking Fajardo Harbor. Abandoned marine cliffs stand back from the shore in line with the original bar. The finest of the east coast beaches are those built across the valleys of the Blanco, Humacao, and Yabucoa rivers.

SOUTH COAST

Along the south coast the waves beat with far less vigor than they do on the north or east coasts, where they are impelled by the steady and powerful northeast trade winds. East of Guayama the headlands are still being attacked, and the small alluvial fillings already described are being cut away; but between Guayama and Ponce the transition from land to sea floor is a most gradual one and only rarely, as south of Guayama, are the modern waves cliffing the stream-laid gravels of the extensive flood plains. West of Guayama practically no cliffing occurs, but there are occasional places where insignificant shore bars have been thrown up. The mangrove-covered flats, known as the Caribes Islands (Fig. 31), appear to have such an origin, and the lagoon lying back of them, known as Jobos Harbor, is exceedingly shallow. It is similar in origin to the Laguna de Las Mareas. Most of the coast, however, exhibits no features which can be ascribed to wave action. The alluvium brought down by

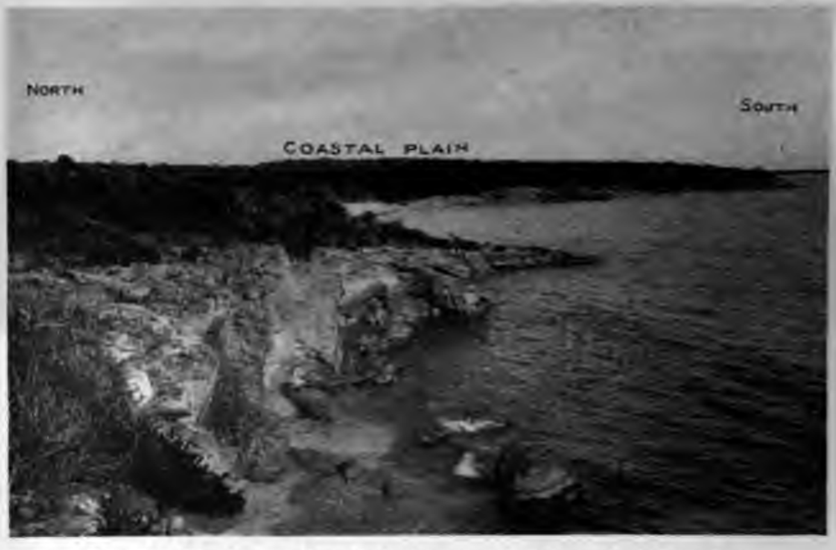


FIG. 32.—*The low southward sloping coastal plain east of Cape Rojo*

The cutting back by the waves has been very slight.

the streams seems to be pushing the shore line seaward against the ineffectual attack of the weak waves.

West of Ponce fewer large streams enter the sea; none at all in the southwest portion of the coast beyond Guanica. The low remnants of the Tertiary coastal plain are cliffed seaward (Fig. 32). The bench offshore is exceedingly shallow for several miles and the waves which reach the land are consequently very weak. Coral colonies apparently isolated provide material which has been thrown up to form low reefs, barely coming to the water's surface.

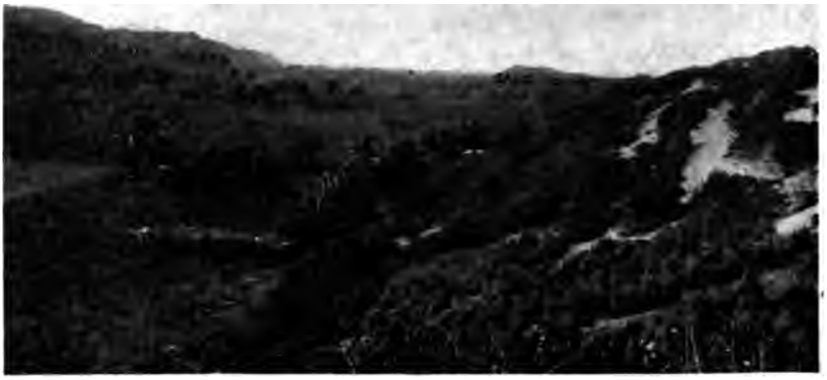


FIG. 33.—*The marine cliff forming the edge of the Tertiary coastal plain on the north coast west of Isabela*

Now protected by a beach one-fourth of a mile in width, which bears along its seaward margin a high ridge of wind-blown sand.

In the vicinity of Cape Rojo the work of the modern waves may be seen in the delicate tracery of beaches connecting two groups of islands with each other and with the mainland. The lagoons thus cut off can best be described as shallow salt flats and are usually known as salinas. These natural evaporating basins have been somewhat improved by artificial methods, and represent one of the three important sources of crude salt now shipped from the tropics. The block diagram of the region (Fig. 5) presents the aspect of the two complex tombolos.

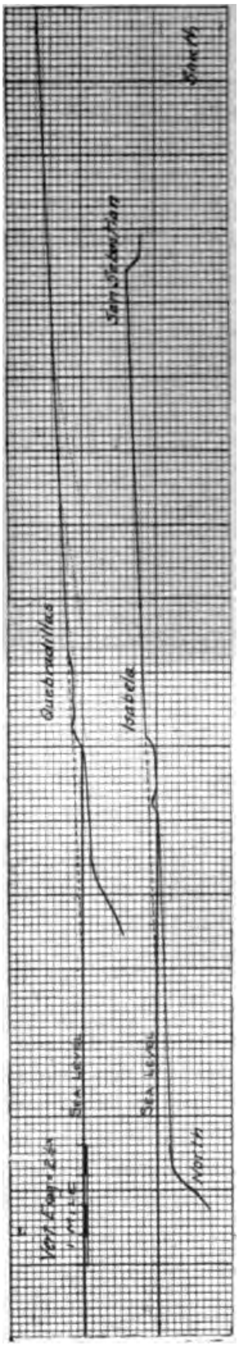


FIG. 34.—North-south profiles through the margin of the coastal plain at Quebradillas and Isabela

WEST COAST

The irregularity consequent upon the drowning of the west coast of Porto Rico has been destroyed by the development of beaches and the filling of the bays. Occasional lagoons still remain, as at Lake Joyuda. The beaches customarily reveal their stages of development by parallel ridges, a feature well marked between Point Guanajibo and Mayaguez. As a whole, the work of the waves along the west coast has produced effects similar to those along the east coast, but cliffing of headlands has been much less pronounced.

NORTH COAST

The north coast from Aguadilla to Camuy is characterized by marine cliffs, averaging over 200 feet in height, cut in the limestone coastal plain. Considerable stretches of these cliffs, however, notably to the west of Isabela, are no longer subject to wave attack, owing to the protecting beaches built in front of them, in places to a width of one-quarter to one-third of a mile (Fig. 33). A protecting beach in front of a marine cliff is a normal feature in the process of wave erosion along a steep coast. It represents a temporary reversal of conditions from those favoring cutting to those favoring deposition and is quite analogous to similar alternations in the life of a stream.

The extent to which the sea has cut back into the Tertiary coastal plain may be estimated by carrying the slope of the plain surface seaward until it meets sealevel. With a slope of 1½ degrees, the distance is approximately two miles. It must be remembered that the outer thin edge of the wedge was easily removed, and it may also be assumed that cutting has been long active and was going on before the period of submergence. Fig. 34 provides two profiles from this part of the coast. The one through Isabela does not need any especial explanation beyond what has just been said. The other profile, through Quebradillas, seems to be anomalous, in that the continuation of the slope of the coastal plain surface meets the sea even beyond the edge of the narrow continental shelf. Two interpretations are possible: first, the dip of the strata is steeper than the slope of the plain surface. If the normal dip of the beds instead of the slope of the plain surface be continued seaward from the cliff, assuming that this is approximately the top of the series, sealevel is reached less than a mile from shore and within the limits of the continental shelf; second, faulting may have taken place at the edge of the continental shelf, so that the Tertiary coastal plain was broken off during uplift. The apparent marine bench, shown in the profile near Quebradillas, standing at an elevation of 150 to 200 feet, has already been explained as being due to differential erosion along bedding planes.

East of Camuy most of the north coast is low and bordered with alluvial deposits. Fringing the shore is a chain of sand dunes exhibiting all stages of consolidation and dissection and in part constituting the San Juan formation about to be described. These sand deposits frequently hold the position of barrier beaches, in which case they have behind them marshy lagoons or open bodies of water. This is the explanation of Lake Tortuguero near Manati, San Juan Harbor, and the smaller lakes of San José, Cangrejos, and Piñones to the east.

The prevailing drift of the water along the north coast is toward the west, as a result of the strong trade winds from the northeast. In the coves between the minor promontories formed by remnants of the San Juan formation secondary eddy currents are developed. These affect the bars at the mouths of streams and serve to deflect the stream outlets toward the east. In Fig. 35 several sketch maps illustrate this tendency in the case of the Bayamon and Cocal rivers and San Fernando Creek near San Juan, and of the Arecibo, Manati, and Cibuco rivers further west. In each instance the mouth of the stream is diverted eastward.

THE SAN JUAN FORMATION

This interesting formation occurs only along the north coast of Porto Rico, and is described by Berkey as a series of solidified or fossil sand dunes dating from the Pleistocene. At San Juan city, which is built upon the formation, its elevation is 100 feet above sealevel. Nowhere else does it rise to quite this height. Almost everywhere associated with the solidified dunes are other dunes of loose sand now forming. Even these unquestionably very recent dunes show tendency toward solidification. Therefore, it is difficult to draw a sharp line between the two types of dunes and, in the opinion of the present writer, there has been an uninterrupted process of dune formation. In a bold way the San Juan formation may be pictured as occupying the position of a broken barrier reef along the north coast, continuing eastward in the Cordilleras Reefs, and finding its easternmost expression in a small mass just off the northwest corner of Culebra Island. Behind the barrier there is usually a marshy lagoon or open body of water, but occasionally the dunes rest directly upon the mainland. The cross-bedded structure is almost everywhere a pronounced feature. In addition there are two or three other features of unique character which apparently demand special explanation.

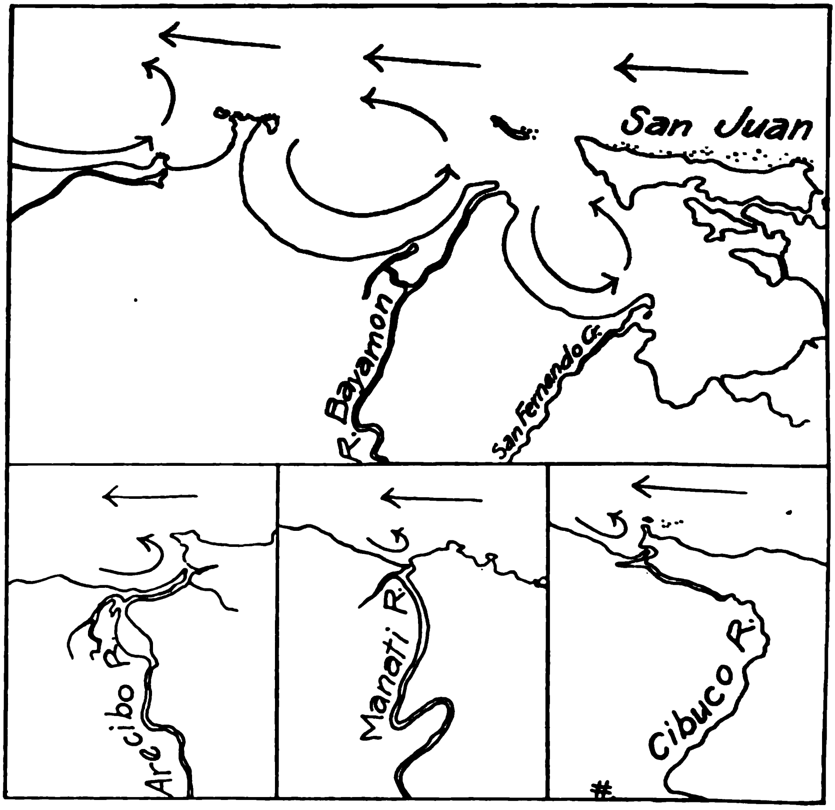


FIG. 35.—*River mouths of the north coast*

Showing the effect of secondary eddy currents in diverting the rivers toward the east.

The first of these exceptional features is to be noted in the cliff of the San Juan formation immediately east of Arecibo. This cliff faces toward the south and overlooks the broad flood plain of the Arecibo River. The cliff face shows the strikingly cross-bedded structure with steep dips characteristic of the San Juan formation; but it shows also a series of horizontal lines crossing the structure, but in no way interfering with it. This unique feature Berkey has suggested was induced by the gradual submergence of the sand dune after formation. He therefore associates it with the oscillation of the coast line believed to have occurred recently in the island's history. The cross-bedding is therefore to be considered the primary structure of the dunes and the horizontal lines a secondary matter. In addition to these horizontal consolidation lines, as they might be termed, there occurs a prominent horizontal layer of sand near the base of the cliff. This layer is unconsolidated and of course interrupts the cross-bedded structure which occurs above and below it. Inasmuch as neither of these two features—that is, neither the horizontal consolidation lines nor the interrupting horizontal layer of sand—is a feature to be noted elsewhere in the San Juan formation, it seems reasonable to believe that a local cause might furnish the necessary explanation. The Arecibo River, which flows not far from the base of the cliff, is a powerful stream and is subject to extreme oscillations of level. It is therefore suggested that the horizontal unconsolidated layer near the base of the exposed part of the formation represents a deposit of alluvium left by the stream upon a part of the sand dune which it had truncated in its endeavor to break through to the coast during heavy floods. The upper cross-bedded part of the formation represents the dune material built upon the alluvium when the river had subsided or altered its course to a different channel. The alluvial layer may therefore be considered a part of the river's flood plain upon which later dune-building has taken place.

The secondary structure or horizontal consolidation lines occurring above this sandy layer may have been induced by subsequent rises in the level of the river so as partly to submerge the more recently built dunes. This is a very probable event, for it is on record that the Arecibo River in heavy floods deeply submerges its flood plain. Such an event is aided by the very narrow outlet to the sea which the river now has between the continuous dune formation on either side. During the heavy floods of 1896 much of the town of Arecibo was submerged, indicating a rise of 20 to 30 feet at that time. A rise of 30 or 40 feet would account for practically all the phenomena now observed. It is to be noted, too, that the secondary horizontal structure is to be observed only on the landward side of the dune in rather close proximity to the river and adjacent to its flood plain. The conclusion, then, regarding the secondary horizontal structure is that it does not necessarily indicate a rise of sealevel. As an alternative explanation the rise of the river level in floods is offered, and it is shown that such an event is a probable occurrence.

Another unique feature of the San Juan formation, and one which the writer has not seen described elsewhere, is the series of small terraces occurring near sealevel and having characteristics which may be briefly summarized as follows:

1. The terraces always occur within the range of present wave action.

2. In appearance the terraces resemble those of the well-known Mammoth Hot Springs in Yellowstone Park.

3. There is no order whatever in the arrangement or size of the terraces.

4. The terraces have not been *cut* by the waves; they have been formed by the precipitation of material around the rims of shallow basins as the water overflowed. This material usually has a pinkish hue and may be easily distinguished from the granular sandstone of the formation.

5. The terraces are practically horizontal.

6. The cross-bedding of the sandstone cuts across the terraces at all angles.

7. Where irregular masses or blocks have fallen into the water, they first assume a very jagged character, but as loose material is filled in and cemented into the crevices, and as the water pouring in and out precipitates lime around the edges, gradually the sharp, angular forms give way to a terraced aspect and the original disordered make-up becomes obscure.

8. Terraces of this type are developed not only in the San Juan formation, but also at the base of the Tertiary limestone cliffs near the west end of the north coast (Fig. 36).

The conclusion from these observations is that consolidation is now rapidly going on in the zone of water action. Other observations along the coast bear out this statement. For instance, it is to be noted that the modern beaches are occasionally firmly cemented like a pavement.

The stone reefs of Brazil described by Branner (1904) is a well-known example of a modern beach now consolidated. Branner suggests that local lithification may be brought about in the following ways:

1. By carbonated rain water dissolving out the lime carbonate in the upper portions of calcareous sands and depositing it in the lower portions.

2. By the escape of carbon dioxide from the sea water when the surf breaks upon the beaches.

3. By the escape of carbon dioxide from sea water where it is warmed by the tropical sun.

4. By the submarine escape of carbon dioxide about volcanic vents.

The first three of these explanations would undoubtedly apply to the consolidation of the sand dunes along the north coast and to the development of the terraces described. In addition to these explanations, it may be noted that spray from the waves is continually being blown inshore for hundreds of feet along the north coast of Porto Rico, so that the seaward side of the dunes is kept moist. The constant evaporation of this sea water and the liberation of carbon dioxide would encourage lithification, especially on the surface of the dunes. Invariably it is that portion of the dunes exposed to the ocean which is most thoroughly lithified. All degrees of lithification are to be noted, from that of a mere crust on the outside of a sand dune, kept moist by the spray from the waves, to that of a hard rock mass so firmly cemented and thoroughly infiltrated as apparently to have lost its original cross-bedded aspect. For this reason there appears to be no satisfactory means of distinguishing the earlier from the more recently formed dunes.

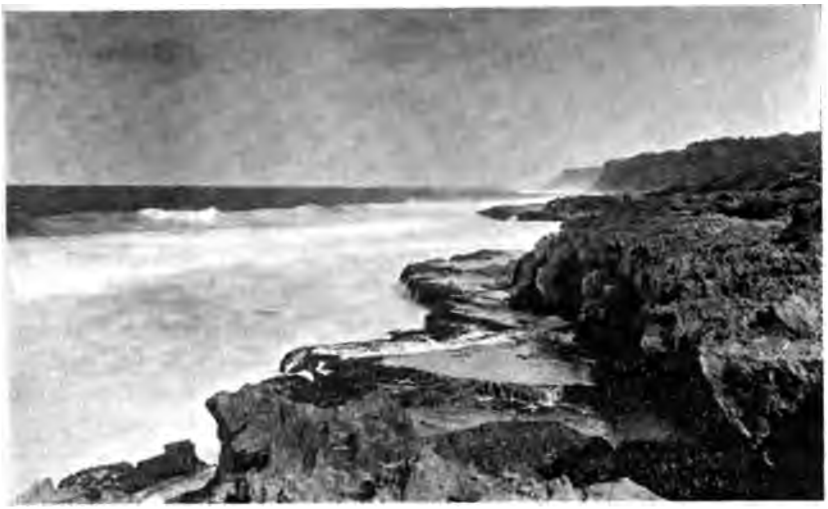


FIG. 36.—*The coast east of Quebradillas*

Showing terraces in the Tertiary coastal plain which resemble in all respects those formed in the San Juan formation. The mode of origin in each case is similar to that of the terraces of the Mammoth Hot Springs.

The original definition of the San Juan formation as proposed by Berkey was meant to apply only to those consolidated dunes along the north coast. Since then, however, other observers have extended the use of this term more or less subconsciously to cover all deposits of a consolidated character or recent age. For instance, the thick coating of onsolidated beach material consisting of coral heads, boulders, gravel nd shells covering the uplifted wave-cut platform of Desecheo Island is onveniently spoken of as the San Juan formation. Likewise the bench f coarse consolidated material fringing the south side of Mona Island, nd the slightly uplifted consolidated beach on Muertos Island, call to nind the San Juan formation. The present writer is in favor of applyng this term to all these occurrences. It is apparently impossible to livide sharply the very recent ones from the older ones or the non-consolidated occurrences from those completely lithified. Nor does it seem xpedient to separate those occurrences which are strictly of dune origin rom those which constitute beaches, so intimately are they associated vith each other.

SUMMARY

The San Juan formation may then be described as the beach material nd its associated dunes, consolidated or unconsolidated, now uplifted or ubmerged, which was formed around the coast of Porto Rico in recent eological time. The chain of islands forming the Cordilleras Reefs runing eastward from Porto Rico toward Culebra may be considered as a eries of dunes capping a wave-cut escarpment. They were formed probbly during the Pleistocene and partly submerged at the end of the glacial period. These dunes would be the earliest representatives of the San Juan formation. Along the north coast of Porto Rico the bordering reefs vith their dunes are essentially barrier beaches. Locally they are being igorously cut away by the waves, and in other places a tendency toward each widening seems to prevail. Where the beaches and dunes are ndergoing wave erosion they commonly are strongly consolidated. This s the case in the central and eastern part of the north coast. Where the eaches are being widened by the addition of material seaward, the growth f new dunes prevails and these in general are not so strongly consolilated. This is the case in the western extremity of the island, north of Isabela, where protecting beaches have been built along the coast at the ase of the earlier formed wave-cut cliffs. Finally, included in the San Juan formation, are the deposits of more or less consolidated beach material capping the uplifted beaches along the shores of Desecheo, Mona, nd Muertos islands and at occasional points on the mainland, as, for nstance, on Rincon Point.

PROBABLE VERY RECENT SLIGHT EMERGENCE

Several kinds of evidence have been noted by different observers favoring a recent emergence of Porto Rico and the smaller islands near by. A study of the region as well as a careful evaluation of the evidence collected by others lead to the conclusion that there has been a recent emergence of not more than 40 feet. Most of the evidence lies in the western half of the region and there is practically no evidence in the eastern part. Some of the evidence presented, indicating an uplift greater than that just mentioned, I believe to be invalid. In the following pages all of the lines of evidence are discussed. They may be essentially grouped as uplifted beach deposits and terraces or benches. The beach deposits occur on Desecheo, Mona, and Muertos islands, and near Point Jiguero and other isolated localities on the mainland. The terraces or benches occur on Desecheo Island and near Quebradillas, Guayama, Point Jiguero, and Mayaguez on the mainland.

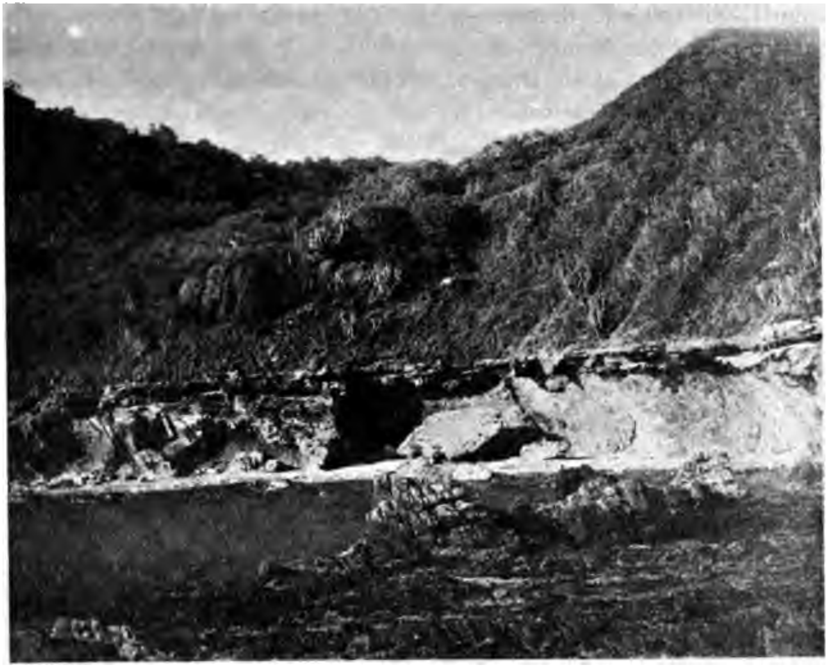


FIG. 37.—*The uplifted beach on the south side of Desecheo Island*

In the foreground may be seen part of the wave-cut platform truncating the older series rocks.

Desecheo Island lies some twelve miles to the west of Point Jiguero and is formed entirely of older series rocks which have been truncated by a wave-cut platform now uplifted to a height of 20 feet above sealevel (Fig. 37). The term "uplift" is used because the common evidence in all the West Indies favors a movement of the land rather than one of the sea. Marine benches and terraces lack a uniformity of elevation in the various islands. The bench on Desecheo intermittently rims the whole island, but is preserved to a greater width and in much better perfection on the south coast. There it may be as much as 100 yards wide, cutting sharply across the upturned edges of the volcanic sediments and ending abruptly on its landward side against the steep hill slopes which are presumably wave-cut cliffs. The platform dips seaward in all directions from the island and thus passes down gradually into the water. The surface of the platform is heavily coated with a thick deposit of consolidated beach material consisting of coral heads, boulders, gravel, and shells. The coral heads appear occasionally to be in position, as though still attached to the places where they grew. The evidence which this island presents surpasses that noted elsewhere and would indicate a minimum uplift of 20 feet.

Mona Island is fifty miles to the southwest of Porto Rico. On its southern side is a platform several hundred yards wide in places. Its surface stands 10 feet or so above sealevel. The platform is composed almost entirely of consolidated beach material consisting of coral heads and modern shells. Its inner margin is made up largely of talus from the limestone cliffs, all thoroughly cemented. The platform is everywhere made up of this heterogeneous material. Nowhere is it a rock platform. Its outer margin, in the zone of water action, shows terraces like those described for the San Juan formation. These terraces are not due to wave cutting, but to the deposition of material around the edges of shallow depressions. Along the southeast coast of Mona Island, a mile or two south of the lighthouse, remnants of the former beach may be seen adhering to the lower portion of large talus blocks standing in the water at the foot of the cliffs. The blocks are as large as a two-story or three-story building. The presence of beach material at their base indicates the extreme recency of uplift. The evidence on Mona Island favors a minimum uplift of five to ten feet. It is certain that the uplift here was less than that on Desecheo.

Fringing the north side of Muertos Island, near Ponce, is a little ledge of fragmental beach material consisting of shells, coral heads, and limestone fragments firmly cemented together (Fig. 38). It is only a few yards wide and stands now some five or six feet above sealevel. The evidence here would suggest an uplift approximating that on Mona Island, but very much less than that on Desecheo.

Near Point Jiguero, Hubbard reports finding consolidated sands and gravels with modern corals and gastropods resting upon the Tertiary at an elevation of 40 to 45 feet above sealevel. A mile south of this point Hubbard reports similar gravels at 35 feet above sealevel. Near the lighthouse the same investigator found sand and gravels with modern shells resting on truncated rocks of the older series at an elevation of six to ten feet. This evidence would appear to favor an uplift in this locality of approximately 40 feet.

At other isolated localities uplifted beach material favors an uplift of 12 to 15 feet. On Point Aguila, forming the southwest corner of Porto Rico, a more or less consolidated layer of shells and beach material rests upon the Tertiary at 10 to 15 feet above sealevel. Near Quebradillas, at the mouth of a small canyon, a bench 15 feet above sealevel and about 50 feet in width is developed upon the Tertiary limestone and is covered with consolidated gravels and coral heads apparently in place. The mere presence of the bench alone is not good evidence of uplift. Differential erosion commonly results in the development of benches in the almost horizontal Tertiary rocks. Near Barceloneta modern shells and large coral heads occur in consolidated gravels at 12 feet above sealevel.

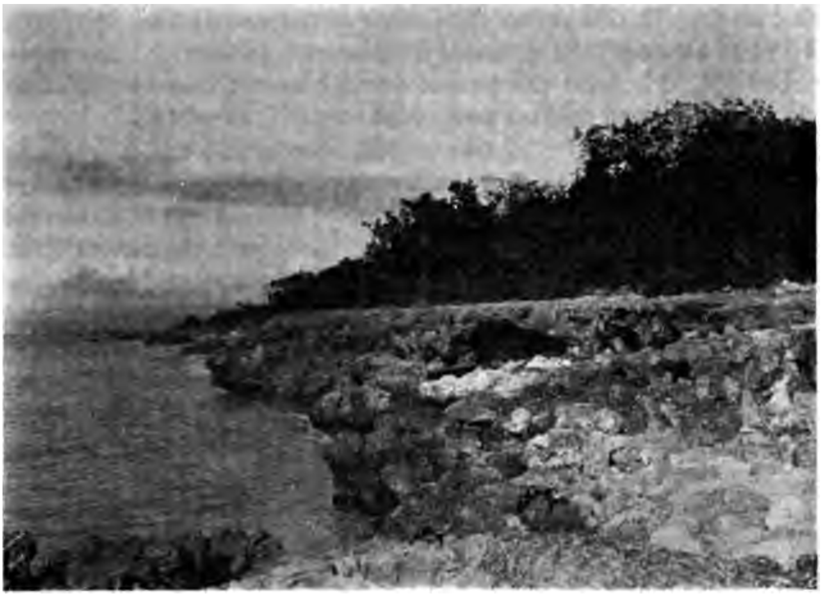


FIG. 38.—*The uplifted beach on Muertos Island*

In the search for uplifted beach material on Porto Rico the investigator must guard against mistaking the numerous occurrences of Indian shell heaps for natural deposits. Usually in these cases fragments of pottery and other criteria, such as black soil, indicative of former camp sites, will reveal the true origin. Such shell heaps were noted near Rincon, Coamo Springs, and on Vieques.

The splendid example on Desecheo Island of a marine bench uplifted 20 feet above sealevel has already been described. Near Quebradillas there is a pronounced terrace (Fig. 16) along the coast, having an elevation of 180 feet above sealevel and a width of one-quarter to one-third of a mile. This terrace is developed upon the almost horizontal Tertiary limestone and it is strongly suggestive of wave planation. The question of its origin, however, has been discussed, and it was pointed out that the terrace is due to the differential erosion of the limestone along the bedding planes. In this region the surface of the coastal plain consists of groups of haystack hills separated by intervening flat areas. It happens that at just this point the present waves have cut back to one of the "flats," and thus an uplifted marine-cut terrace is simulated.

Part of the town of Guayama is built upon rock terraces, which apparently stand slightly above the alluvium deposits of the playas or flood plains. Berkey (1915, p. 48) has interpreted these as due to marine cutting. A careful study of this locality, however, leads the present writer to the conclusion that their flat surfaces have been produced by the planing action of the stream which deposited the alluvium, in this instance the Guamani River. The reasons for this belief may be briefly summed up as follows:

1. The rock terraces lie in the mouth of the valley of the Guamani River and may be traced upstream between the valley walls.

2. The surface of the terraces stands approximately at the same elevation (180 feet) as the surface of the highest part of the alluvial plains and the slope of the two is practically identical. Much of the alluvial plain has been recently cut away by the river. Those regions consisting of hard rock stand up now as terraces.

3. Parts of the terraces are covered with angular gravel exactly like the material composing the alluvial fans.

4. There is no cliffing of the mountain spurs back of the terraces.

5. Flat rock surfaces of similar character are to be observed elsewhere, as along the lower course of the Jueyes River, so intimately related with the alluvial deposits as to leave no doubt that they were formed at the same time the alluvium was laid down.

6. The rocks of the older series are so much decayed that in numerous places throughout Porto Rico they are being beveled across by the streams on their present flood plains.

7. Similar truncating and planation of strata by streams at the point

where they emerge from a mountainous area is to be noted in other parts of the world. For instance, near Cody, Wyoming, where the Shoshone River emerges from its canyon, there is a splendid terrace whose surface bevels across dipping strata. In this case no agent other than the river could have been operative. Similar conditions are to be noted in the Ortiz Mountains of New Mexico. The conclusion regarding the Guayama rock terraces is that they are river-cut and do not represent an uplifted marine bench.

A small terrace occurs at Point Jiguero, its inner margin standing some 80 feet above sealevel. Because it holds a position near the mouth of a stream, somewhat similar to those at Guayama, it may have been formed in a similar way. Moreover, it is developed upon almost horizontal beds of Tertiary limestone, and the strong tendency toward the development of flat areas by differential erosion would somewhat favor such an explanation. Its position along the coast gives it the aspect of a marine-cut bench, but consideration of other factors just mentioned favors considering it as due to stream origin.

Near the Reform School, just south of Mayaguez, a narrow bench, standing 12 to 15 feet above sealevel, can apparently be ascribed to no origin other than that of wave planation. It truncates the older formations, but a search did not reveal the presence of beach material.

Most of the evidence cited would indicate an uplift less than 20 feet. Apparently the greatest uplift indicated is at Point Jiguero, where Hubbard finds beach material as high as 35 to 40 feet above sealevel. The easternmost piece of evidence noted was on Muertos Island, 50 miles to the east of Point Jiguero, where the uplift was considerably under 10 feet. The eastern end of Porto Rico and the islands to the east nowhere revealed any indication of recent change of sealevel. The westernmost evidence was on Mona Island, some 50 miles west of Point Jiguero, where a modest uplift of 10 feet or so was indicated. Nowhere are there displayed series of terraces similar to the splendid examples featuring the coast of Cuba.

BRIEF NOTES ON ADJACENT ISLANDS

Desecheo

This small island, lying 12 miles to the west of Porto Rico, is almost circular in shape and has a diameter of about one mile. It is made up entirely of older series rocks, striking almost east-west, but crossed by joint systems which in general run transverse to the structure. The little harbor providing a refuge on the south coast appears to be developed along such a joint plane, to which is due also the valley in the hills above. Around the base of the island is an uplifted wave-cut platform and beach, having its inner margin 20 feet above sealevel. This has been described in the preceding pages and is illustrated in Fig. 37, which also shows a part of the small harbor and the valley above.

No flowing streams are to be found on the island. The extremely dry conditions favor an extensive growth of cactus, although a forest of medium-sized trees covers many of the slopes. A brief but interesting account of the vegetation of the island has been given by Dr. N. L. Britton (1914).

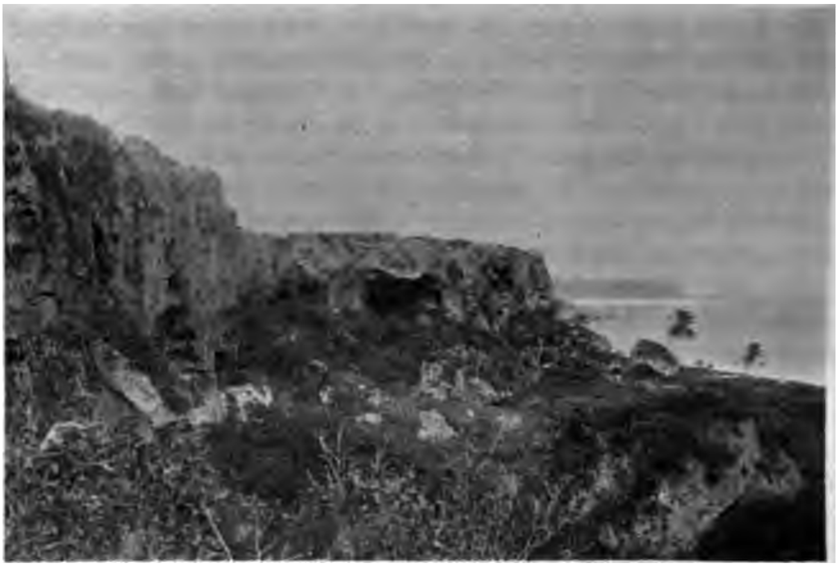


FIG. 39.—*East coast of Mona Island*

Showing its plateau character and some of the caves which honeycomb it.

MONA

Mona Island, 50 miles to the southwest, is not within sight of Porto Rico except from the higher summits, and it then appears as a low haze on the horizon. This island, as well as its little neighbor, Monita Island, is a remnant of the Tertiary, having an almost horizontal surface, which ends abruptly on all sides in cliffs 150 to 200 feet above the sea. Though, in general, circular in shape, its outline is angular, a feature due to the jointing which divides the limestone into large blocks. The entire island is literally honeycombed with caves (Fig. 39). These are developed in one of the more soluble limestone layers outcropping about 75 feet above the sea and form one of the important sources of guano in the Porto Rico district. Along the southwest coast there appears good evidence of recent uplift in the narrow platform at the base of the cliffs. It stands 10 feet or so above sealevel, has a width of several hundred yards, and consists of consolidated beach material containing coral heads and modern shells. The inner margin of the platform is made up of talus from the limestone cliffs, thoroughly cemented. The outer margin, in the zone of wave activity, shows terraces at the water level like those described for the San Juan formation. Along the southeast coast, a mile or two south of the lighthouse, remnants of the former beach still appear adhering to the base of large talus blocks standing in the water at the foot of the cliffs.

There is practically no soil on the island, and passage over the top of the plateau is arduous in the extreme on account of the sharp and jagged surface of the limestone and the abundant growth of cactus. The only water is that from the rain which accumulates in the slight irregularities on the surface of the rock. Over this forbidding country there roam small herds of wild goats, cattle, and pigs which have escaped from domestication and have taken on characteristics in keeping with the harsh conditions of life to which they are now subjected. For instance, the pigs have apparently reverted to a type of boar. Prominent tusks, two or three inches long, were noted on one which had been captured. The animal is so vicious that the natives always carry their long, sharp machetes for self-protection. Besides the lighthouse, a small temporary camp is located on the island for the workmen who are employed in removing the guano from the caves. These people supply themselves with fresh meat by hunting, a wild goat or two being the usual result of their efforts.

VIEQUES

The narrow channel between Vieques and the eastern coast of Porto Rico is nowhere more than 60 feet in depth and in general is a great deal less. This island, like Culebra, was presumably separated from the mainland as a result of submergence. It is low-lying and is made up mainly of the oldland rocks. These are flanked on the east end and south side by remnants of the Tertiary coastal plain. A well-formed cuesta has been developed, and the subsequent drowning of the island has permitted the sea to enter the inner lowland at several places along the south coast. Some facts regarding the Tertiary coastal plain have already been given. The accompanying diagram (Fig. 40) is a sketch drawn looking south from near Culebra Island and conveys a fair idea of the general aspect of

Vieques. Among the minor features of interest are the alluvial deposits clogging the valleys on both the north and south sides, resembling those near Yeguas Point on the southeast corner of Porto Rico. At Playa Grande a graceful and picturesque beach has been thrown across one of the drowned bays which has not yet been filled with alluvium. The low headlands throughout the coast are being cliffed by the waves.

In general the island is dry, as evidenced by the common occurrence of cactus, although it is not at all barren. The raising of cattle is the most important industry in the hilly parts, but the broad inner lowland on the south side, as well as extensive tracts on the north, are devoted to the production of sugar-cane.

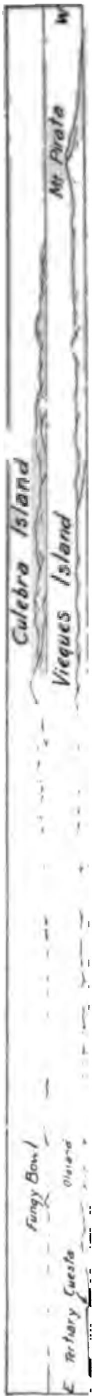


FIG. 40.- Sketch of Culebra and Vieques Island
Vieques from the north, Culebra from the south.

CULEBRA

Culebra and its numerous adjacent cays is represented wholly by the oldland rocks, which are moderately folded, although no prevailing trend in the structure was noted. The salient features of the topography are controlled by erosion along strong joint systems, the major one running in a northwest-southeast direction and a minor one almost transverse thereto. Great Harbor and Flamingo Bay are valleys developed along the line of the major system and later drowned. This island exhibits the customary features due to drowning. Deep bays indent its coast and numerous islets lie offshore. The head of Flamingo Bay has been cut off from the sea by a beautiful beach, and owing to the small size and intermittent character of the contributary streams the lagoon is but slowly being filled with alluvium.

There is now only a small settlement on this island, which was formerly an important coaling station for the United States Navy. Dairying and the raising of cattle appear to be the only industries. No sugar-cane is grown here.

MUERTOS

The Caha de Muertos (Fig. 41), or the "box for the dead," is a coffin-shaped remnant of the Tertiary coastal plain lying offshore from Ponce. An islet at its west end is made up of steeply tilted rocks of the older series, sharply planed across by a platform over which at one time the Tertiary beds undoubtedly extended. Along the south shore of the larger island the older rocks outcrop. Presumably the island consists of a base of oldland rocks capped by a layer of the coastal plain limestone 100 to 200 feet thick. Apparently the presence of the more resistant old rocks at

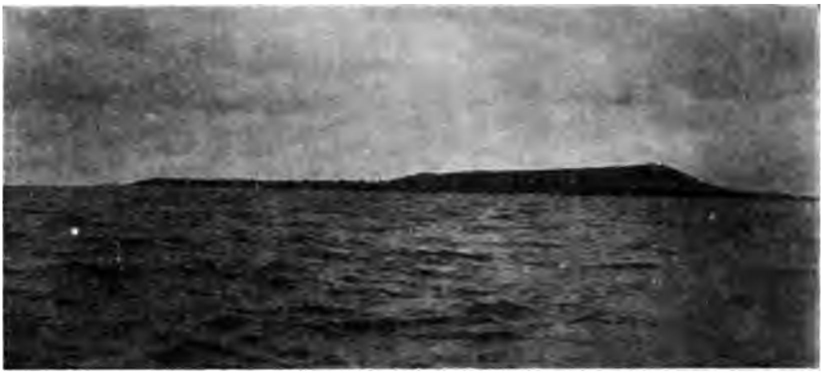


FIG. 41.—*Muertos Island from the north*

the base has prevented the destruction of the island by the waves. The north shore is fringed with what appears to be an uplifted beach of consolidated limestone fragments, shells, and coral heads, now standing five to six feet above sealevel (Fig. 38).

ACKNOWLEDGMENTS

The field-work on this problem occupied a period of five months, from September 1, 1916, to February 1, 1917, and constitutes one of the special studies of Porto Rico carried on by the New York Academy of Sciences. To Dr. C. P. Berkey I am personally grateful for the kindly aid and faith which he showed in the undertaking. The other members of the Department of Geology of Columbia University have taken abundant interest in the problem, and I use this opportunity to express my high regard for all of their suggestions. I am especially appreciative of the encouragement and inspiration rendered by Dr. Douglas W. Johnson and for his untiring and critical advice.

The officials of the Porto Rican Government have been most courteous in helping to overcome some of the difficulties in the field, and I desire to acknowledge the aid afforded by Governor Yaeger in the matter of transportation and of Colonel Shanton, Chief of the Insular Police, in presenting me with testimonials to his various officers.

Finally, I am more than pleased to include the name of Mr. Fernando Oliver, of Añasco, whose perseverance and pluck during three months of arduous work in the capacity of interpreter and assistant are deserving of mention.

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ERRATA

Page 58, line 33, and page 59, line 8, read *Metis* for *Metris*

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